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Resource-Independent Computer Aided Inspection

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Resource-Independent Computer Aided Inspection

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ABSTRACT

Quality is of paramount importance when establishing and maintaining market share in any manufacturing sector. Measurement is a critical tool in ensuring product conformance and is a major enabler in the control of manufacturing processes to improve and maintain quality. Furthermore, measurement is evolving into a value-adding process in its own right and the gained measurement knowledge has become crucial for both design and manufacturing stages. Despite this ever increasing importance, measurement planning and execution is still carried out with great reliance on manual operations and ambiguous practice guidelines utilising tools and software that are very specific to the individual pieces of equipment used in the measurement process. In addition, in industry, measurement plans are defined in isolation instead of in an integrated and interoperable manner with other manufacturing activities.

This research aims to formulate an interoperable integration framework for defining measurement processes through the introduction and realisation of resource-independent measurement specifications (REIMS). REIMS is a data model that represents both measurement features and operations to enable their exchange between computer aided for x (CAx) applications. REIMS enables measurement process definitions to be exchanged between various measurement geographical locations and resources within a distributed manufacturing system. It, therefore, reduces the recently identified variability due to the measurement planning phase that varies depending on the experience and skills of the measurement operators. REIMS also removes an integration barrier at the measurement planning-execution interface and assists in obtaining consistent measurement knowledge. Comparable measurement knowledge is crucial for taking proper decisions for improving both design and machining phases.

This thesis uses system engineering methods for analysing the measurement process and its data flow and requirements. As a result of this analysis, the REIMS data model has been developed based on the STEP modelling and implementation mechanisms to formulate a computer interpretable format of the measurement process data. STEP-based methods have been selected as the framework as they have been previously validated for interoperable data exchange between design and machining applications. The theoretical basis of REIMS is the concepts and definitions presented in the ISO standardised documents for “geometric product specifications (ISO GPS)” as these documents, for the first time in the domain, consider design specifications and measurement activities in relation to each other.

The REIMS data model has been realised and a prototype implementation has been designed utilising the CTC-01 test case encoded as an ISO10303-242 compliant model. This test case has previously been used by the national institute of standards and technology (NIST) for validating the exchange of design data including product manufacturing information (PMI) between different CAD systems and as such provides an authoritative example. The implementation framework uses C++ and ST-Developer to obtain the design information from the AP242 file data and demonstrates the ability of the REIMS data model to map design specifications into measurement features and to define the necessary measurement operations to complete the process definition. An ISO10303-21 compliant file has then been constructed from the REIMS data to establish the proposed data exchange mechanism.

Based on the findings of this thesis, the REIMS provides a coherent, comprehensive and flexible framework for representing the measurement process. Through adoption of REIMS as the standardised framework for measurement planning, companies could ensure the consistency of the measurement knowledge that is gained and maintained in the enterprise regardless of the location or equipment. This would facilitate the spread the measurement process benefits throughout the digital factory with potential for cost saving due to resource fluidity, a significant decrease in plan translation errors and reducing the equipment specific training requirements.

Lovingly dedicated to my dear parents, my beloved wife May and my children Noor and Omar

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LIST of ABBREVIATIONS

1D	One-Dimensional
2D	Two-dimensional
3D	Three-Dimensional
AAM	Application Activity Model
AIAG	Automotive Industries Action Group
AICs	Application Interpreted Constructs
AIM	Application Interpreted Model
ALPS	A Language for Process Specification
AM	Application Modules
ANSI	American National Standards Institute
API	Application Programming Interface
APs	Application Protocols
ARM	Application Reference Model
ASME	American Society of Mechanical Engineering
B-rep	Boundary Representation
CAD	Computer Aided Design
CAI	Computer Aided Inspection
CAIP	Computer Aided Inspection Planning
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAT	Computer Aided Tolerancing
CAx	Computer Aided for x application
CAx-IF	CAx Implementation Forum
CIM	Computer integrated Manufacturing
CLM	Closed Loop Manufacturing
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CSG	Constructive Solid Geometry
CT	Category Theory
CZ	Combined Zone
DET	Digital Enterprise Technology
DIS	Draft of International Standard
DLL	Dynamic Link Library
DMIS	Dimensional Measurement Interface Standard
DML	Dimensional Markup Language
DMSC	Dimensional Metrology Standards Consortium
DoF	Degrees of Freedom
FBD	Feature Based Design
FBICS	Feature-Based Inspection and Control System
FoS	Feature of Size
FRTZF	Feature Relating Tolerance Zone Framework
GAMS	General Algebraic Modelling System
GD&T	Geometric Dimensioning and Tolerancing
GPS	Geometric Product Specifications
GT	Group Technology

HTTP	Hypertext Transfer Protocol
I++DME	I plus plus Dimensional Measurement Interface
ICF	Inspection Control Fragment
IDE	Integrated Development Environment
IDEF0	Icam Definition for Function Modelling
IFCIA	Inspection Framework for Concurrent Information Access
IGES	Initial Graphics Exchange Specification (IGES)
IR	Integrated Resources
ISO	International Organization for Standardization
IUA	Interactive User Interface
LMR	Least Material Requirement
LS	Least Squares
MBD	Model Based Definition
MBE	Model Based Engineering
MCs	Measurement characteristics
MEP	Measurement Execution Program
MIPT	Metrology Interoperability Project Team
MMR	Maximum Material Requirement
MRI	Measurement Resource Information
MVS	Microsoft Visual Studio
NIST	National Institute of Standards and Technology
NPL	National Physical Laboratory
OMI	On-Machine Inspection
PDES	Product Data Exchange Specification
PLM	Product Life Management
PLTZF	Pattern-Locating Tolerance Zone Frame
PM	Productive Metrology
PMI	Product Manufacturing Information
QIF	Quality Information Framework
QMP	Quality Measurement Plan
QMR	Quality Measurement Results
RC	Resource Construct
REIMS	Resource Independent Measurement Specification
REIMS-PI	REIMS Prototype Implementation
RPP	Reconfigurable Process Planning
SCTF-graph	Super-Constraint-Tolerance-Feature graph
SDAI	Standard Data Access Interface
SDK	Software Development Kit
SME	Society of Manufacturing Engineering
STEP	Standard for the Exchange of Product model data
STEP-NC	Standard for the Exchange of Product model data-Numerical Control
SZ	Separate Zone
TC	Technical Committee
TED	Theoretical Exact Dimension
TRL	Technology Readiness level
TSP	Travel Salesman Problem
UF	United Feature

UPR	Undulations per revolution
UZ	Unequal Zone
XML	Extensible Modelling Language
XSDL	XML Schema Definition Language

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Bounce Tolerance	It is an additional tolerance that is allowed for the toleranced feature of size when the actual value of its size parameter deviates from a specified material condition size.
Characteristic Evaluation	It is a measurement process where the actual deviation of an actual feature from its reference entity is determined and compared to the design specification to test the feature conformance to specifications.
Combined Uncertainty	Considering the overall uncertainty in the product life cycle as a combined set of uncertainties. This includes the correlation uncertainty, the specification uncertainty, the method uncertainty and the measurement process uncertainty.
Computer Aided applications	The Deployment of the computers and IT technologies to support different manufacturing applications such as design, machining, planning , inspection, etc.
Computer Integrated Manufacturing	The manufacturing approach of using computers to control the entire production process. This control is done through a production model by which all elements of the factory (i.e., people, equipment, materials, and computers) are organised and integrated around common data repositories.
Construction	The evaluation of ideal feature parameters given other actual or nominal features' data.
Correlation uncertainty	Represents the degree of conformability between functional requirements and stated design specifications, as the correlation uncertainty increases the lack of conformability increases respectively.
Datum	Theoretically exact point, axis, line, plane or combination thereof derived from the theoretical datum feature simulator.
Datum Alignment	The process of matching a part coordinate system to the used measurement machine coordinate system before starting the actual measurement procedures.
Datum simulator	It can be theoretically the ideal boundary used to establish a datum from a specified datum feature or it can be physically the physical boundary used to establish a simulated datum from a specified datum feature.
Digital Enterprise Technology	The collection of systems and methods for the digital modelling of the global product development and realisation processes, in the context of lifecycle management.
Digital Thread	Application of modelling and simulation tools to represent, virtualise and link all the product life cycle activities in a digital manufacturing environment. This aimed to allow more competitive, dynamic and responsive manufacturing systems.
Digitalisation	The integration of digital technologies in manufacturing systems through the digitisation of its components. This is achieved by applying information theory and systems to represent all the

	information within the manufacturing environment in a digital manner. In the context of metrology, Digitalisation also means the conversion of a real object into digital models using different digitalisation technologies.
Execution	A coordinate metrology phase in which a measurement plane is followed by a measurement equipment to gather data from a physical part.
Extraction	A coordinate metrology process to get point data out of the physical part surface by applying specific measurement technology.
Filtering	A processing measurement operation that removes unnecessary information from the extracted data according to a specific measurement scope
Fitting or Association	The construction of a specified ideal geometry to a set of actually extracted point data based on specific fitting criteria and with respect to defined constraints if exist.
Internet of Things	A proposed development that aims to allow network connectivity of everyday objects, thus enabling them to send and receive data.
Interoperability	The ability to seamlessly transfer information from one computer system to another, while maintaining the integrity of the information.
Interoperable integration	It is to integrate defined subsystems together to form one functional system that ensures the seamless and accurate data exchange between its subsystems
Measurement uncertainty	An estimate that characterising the range of values within which the true value of a measurand lies with specified level of confidence. This range exists due to the metrological characteristics of the used technologies or the variability in other factors such as environmental conditions
Method uncertainty	Represents the degree of variation resulted from the misunderstanding and wrong interpretation of actual specifications within verification activities. Incompleteness or ambiguity of design specifications is the main reason for the method uncertainty.
Model Based Definition	A complete 3D digital definition of products and assemblies includes information such as geometry, topology, PMI and saved views.
Model Based Engineering	A systems engineering methodology that focuses on creating and exploiting domain models as the primary means of information exchange between engineers, rather than on document-based information exchange.
Open Standards	Data structures used for sharing public data among various applications and reflects the common or standardised field practice and knowledge
Product Lifecycle Management	The business activity of managing a company's products all the way across their entire lifecycles, from the very first idea for a product through to disposal, reuse, or recycling in the most effective manner.

Registration	A processing measurement operation that aligns many scanned data together into one data set using reference points that are determined manually or using pre-established targets.
Related characteristics	It is a design characteristic that is defined with respect to a datum system
Situation feature	A reduced feature form that determines the location and orientation of its parent feature.
Skin Model	A model that represents the actual part boundaries that could result from the different machining processes
Specification uncertainty	Quantifies the ambiguity and incompleteness in the designer published specifications. This can be due to lack of standard rules and tools or designer's lack of knowledge in applying standards tools.
System Engineering	Interdisciplinary field of engineering that focuses on how to design and manage complex engineering systems over their life cycles to meets customers' needs.
Traceability	The measurement traceability is a property of a measurement result, whereby it can be related to appropriate international measurement standards through an unbroken chain of comparisons or subsequent calibration processes. On the other hand, the measurement information traceability is the ability to identify an unbroken chain between a measurement information and the various causes that can affect it.
Validation	The process of checking whether the specification captures the customer's needs.
Verification	The process of checking that the final product meets the specification.
View dependent specification	It is a design characteristic that requires the identification of the drawing view it is specified in to complete its semantic

1. Introduction

Globalisation and mass customisation are the aspects that characterise, but challenge the modern manufacturing business (Elmaraghy *et al.* 2013; Xu *et al.* 2010; Maropoulos and Ceglarek 2010). Current market gains increased interest toward lowering both products' cost and production quantities. These characteristics are accompanied by increased quality and customisation requirements. Moreover, the present product realisation business is achieved through collaboration between worldwide-distributed organisations that deploy a complex cluster of different hardware and software to accommodate different preferences (Qin *et al.* 2015; Xu *et al.* 2010). Accordingly, this complex industrial environment requires the manufacturing systems to be integrated, adaptable, flexible and automated. These characteristics increase the manufacturing system's competitiveness and its ability to cope with the evolved manufacturing paradigms from traditional manufacturing towards modern digital manufacturing.

Digitalisation principles and the recent shifts in both computing and management technologies are the primary drivers to achieve this digital manufacturing environment, which is based on digital communications between different components of the manufacturing system (Feeney *et al.* 2015). In fact, digitalisation has been named as the third industrial revolution following the technological change caused by mechanisation and assembly lines (Markillie 2012). The terms used today such as "digital thread", "industry 4.0", "Internet of Things" and "connected manufacturing" are all based on digitalisation that provides a smooth information flow between various digital systems (Hartmann *et al.* 2015; Nanry *et al.* 2015).

These modern technologies and developments also enable, support and extend the product lifecycle management (PLM) philosophy. PLM is the business activity of managing a product effectively throughout its lifecycle, starting from the first idea until its disposal (Stark 2011), or its remanufacturing. Computers, information models and databases are the key enablers for realising the PLM philosophy. Computer Aided x (CAx) applications are digital tools that are extensively adopted within this PLM scope. For instance, CAx applications assist the design, machining, assembly and measurement practices. They do so through the processing and exchanging of application data (Pfeifer *et al.* 2006). The transformative potential of the revolutionary digital manufacturing era is indispensably dependent on open and interoperable CAx applications (Nanry *et al.* 2015).

This integration is essential to assist the downstream applications and the decision-making processes. Furthermore, integrated systems should be designed in an interoperable manner to benefit from potential operational and economic throughput (Lipman and Lubell 2015; Feeney *et al.* 2015). Interoperability is the accurate, lossless and seamless information flow between different software systems (Nassehi 2007). It could be achieved by applying open standards that reflect the intended field expertise and knowledge (Zhao *et al.* 2011a; Xu and Nee 2009). The open standards are those data structures used for sharing public data among various applications (Zhao *et al.* 2011a). The lack of interoperability can hamper manufacturing enterprises and lower competitiveness. Interoperable integration aims to replace the currently applied translators between the different proprietary data formats of computer applications. These translators cause a loss in the translated data in addition to the increase in the costly, tedious and time-consuming efforts (Savio *et al.* 2014). The interoperable integration likewise endeavours to eliminate the single supplier solutions that restrict the customer's choice of software and hardware components.

Computer aided design (CAD) and computer aided manufacturing (CAM) systems have achieved an appropriate level of interoperable integration between the design and machining stages. Today, there are standard formats used commercially for representing and exchanging products and machining processes information in addition to good practise guides and conformance testing for the commercial implementations of these standardised data formats. Conversely, the current computer aided inspection (CAI) systems fall short of the interoperable integration needs (Savio *et al.* 2014; Zhao *et al.* 2011b). Measurement departments are still suffering from the inconsistent planning and programming of digital applications and interfaces. Therefore, a new paradigm shift is required to realise an interoperable and integrated measurement system. The need for this new paradigm becomes clearer today to both academic and standard communities, particularly after the economic benefits of measurement interoperability has begun to be realised in the wider manufacturing sector (Savio *et al.* 2016; Savio *et al.* 2014).

This research pushes the boundaries of current measurement integration. As the measurement system is complicated, has many stages and integration interfaces, this introductory chapter will continue by defining and analysing the measurement system in section 1.1 and section 1.2 respectively. The definition of the measurement system stages and their connecting data interfaces is necessary for highlighting the current measurement integration barriers, in addition, to state the scope, aims and objectives of this work correctly. This chapter then ends with section1.3 presenting the overall thesis structure.

1.1. Integration of coordinate metrology within PLM

Dimensional metrology is one component of the verification and validation stage in the products' realisation chain. It is a physical verification step for testing the conformance of a product to the design intent represented as a set of design specifications. Moreover, the measurement data is considered as an enabler for controlling different manufacturing processes (Morse *et al.* 2016). Dimensional metrology has evolved over time by the introduction of advanced computational tools and the application of computer control principles to measurement equipment. In addition, technologies of measurement sensors have also significantly developed (Weckenmann *et al.* 2009; Savio *et al.* 2007), which makes the measurement process more complicated and technology-dependent.

Today, the term coordinate metrology has replaced the traditional dimensional metrology term. Coordinate metrology has also substituted hard surfaces and gauges by mathematically computed surfaces based on a sampled clouds of points that represent the actual physical part surfaces via the use of a specific measurement sensor technology. The reason for neglecting the coordinate measurement integration during the past decades is mainly due to the contested belief that metrology is not a value-adding process and is ultimately, a waste that requires elimination (Hocken and Pereira 2012; Zhao *et al.* 2011a). The opposing view is that measurement adds value by providing the necessary knowledge about manufacturing products and processes (Hocken and Pereira 2012; Savio 2012; Kunzmann *et al.* 2005). Zhu *et al.* (2013) support this view as knowledge gained by measurement also enables the process plans to be of a dynamic nature. Figure 1-1 shows the knowledge gained through the measurement stage as a mean to close both the design and machining loops.

Today, the use of measurement knowledge in both manufacturing and design processes has become crucial, especially in high-value manufacturing systems. The knowledge gained through measurement facilitates the controlling of manufacturing processes such as machining and assembly operations. Furthermore, measurement knowledge assists the designers by increasing their awareness and confidence in the capabilities of manufacturing processes used to produce their designs (Söderberg *et al.* 2016). Quantifying such capabilities by measurement may result in using more relaxed part specifications to accommodate better-known errors of manufacturing processes.

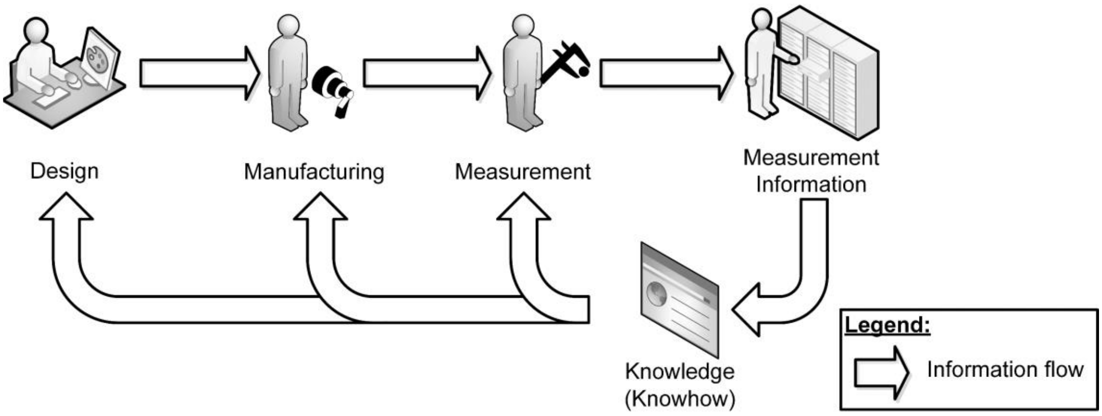


Figure 1-1: Measurement information closes the design and manufacturing loop

Figure 1-2 shows the information flow within the manufacturing system including the measurement stage to clarify the value-adding path of the measurement process. It should be noted that what is not considered as the value-adding from the manufacture's perspective can be considered as an added value from the consumer's perspective when considering improved design or from the cost reduction point of view when considering the control of the machining processes.

Figure 1-2 emphasises that the quality of gained knowledge via measurement data is required to be consistent from one place to another. This consistency is important to reduce the expected uncertainties in the following decisions taken based on this gained knowledge about products or processes. Recently, the international organisation of standardisation (ISO) recognised that variability in the definition of measurement processes contributes to the overall manufacturing process uncertainty as reported in ISO 17540-2 (ISO 2012c). The variability in the measurement process definition directly

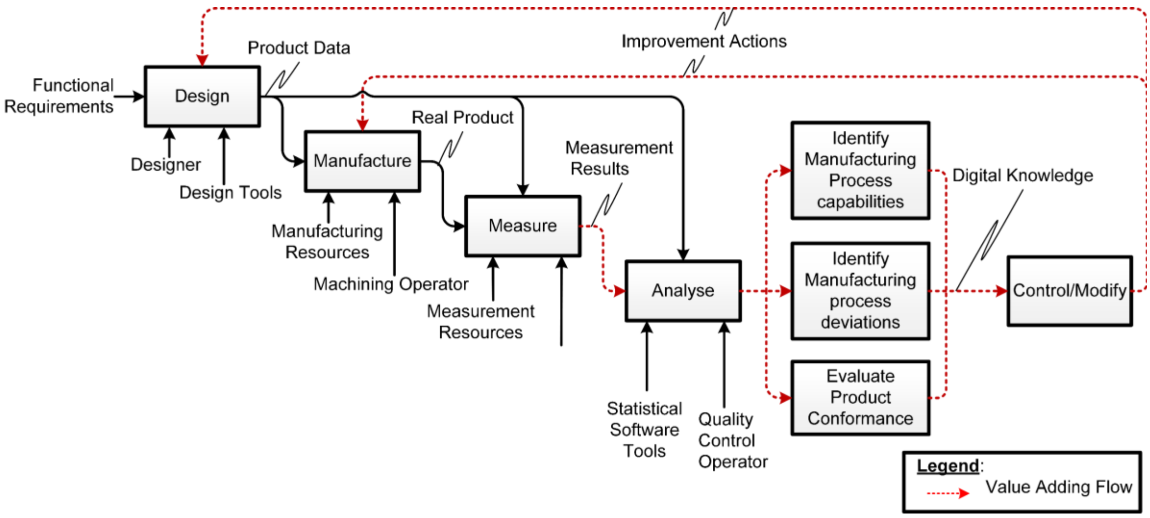


Figure 1-2: The role of the measurement process within the product lifecycle

affects the consistency of the gained measurement knowledge and hence is addressed by this research to be reduced or eliminated.

In fact, measurement planning is a chief source of variability because of the involved operator-based decisions, which is mainly due to its lack of integration. In addition, measurement planning is complex by nature due to the various applied measurement methods, procedures and rules. The measurement planning is considered as one inspection administrative activity in addition to the measurement data acquisition and analysis (Pfeifer *et al.* 2006).

At present, measurement practice is done through different computer aided applications, which involves many manual interactions and decisions. Figure 1-3 shows the main conceptual elements of the CAI applications to perform the intended support functions such as user interfaces, algorithms and databases. Algorithms are used for manipulating and processing the data stored in databases based on a well-defined data model. Algorithms represent the rules and logic of the modelled field knowledge and expertise. On the other hand, databases are the designed storage spaces that allow the saving and the retrieval of the required data using different inference mechanisms. Data

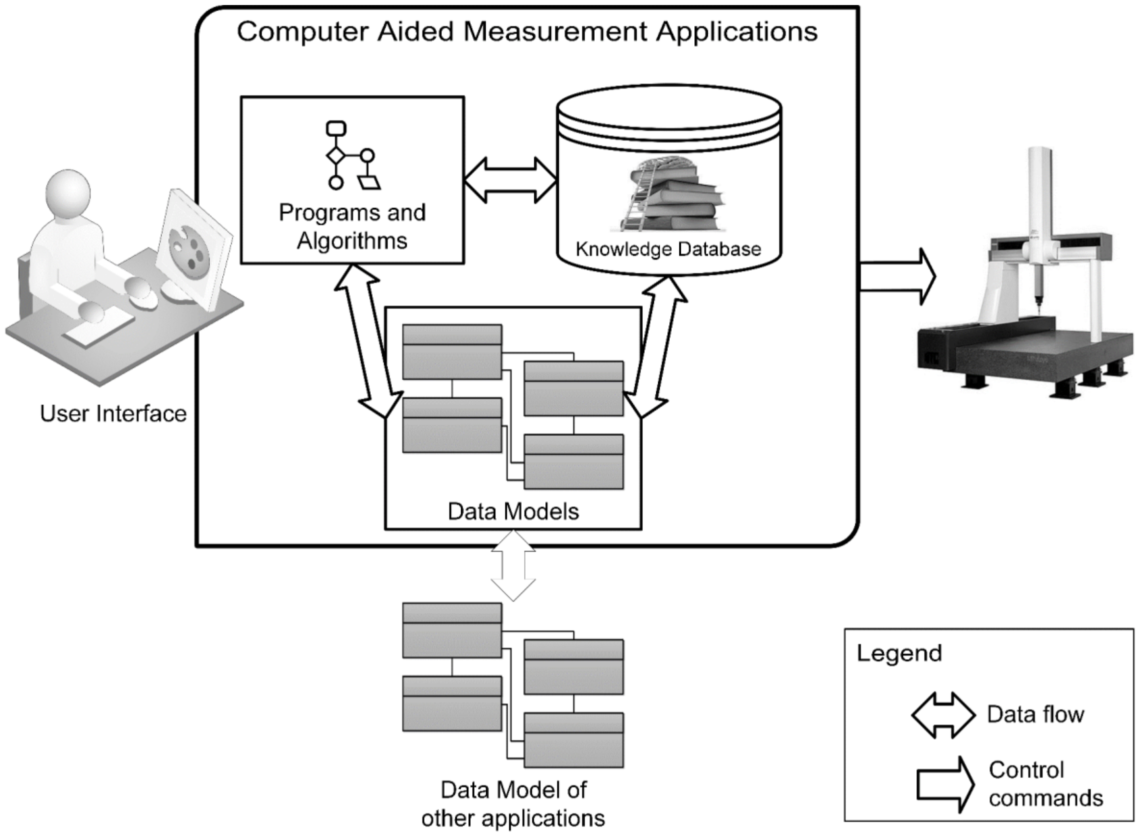


Figure 1-3: Conceptual components of computer aided measurement

models are the designed data requirements necessary to serve the objectives of a particular software application; these requirements include, for example, the specification of data types, relationships, inheritance and rules. Data models hold the data, send it or receive it from the databases; or even among different applications, which is then known as data exchange.

1.2. Analysis of coordinate metrology systems

The analysis of the measurement system identifies where the included integration interfaces within the measurement system are, being either internally between different measurement process stages or externally with other tasks of a manufacturing system. Measurement system analysis means the exploration of its components, interfaces, activities, information, standards and specifications. The NIST (2001) report illustrated the architecture of dimensional metrology activities in integrated systems. Later, in 2004, the measurement interoperability challenge and the applied standards at the different interfaces were discussed, by the Automotive Industries Action Group (AIAG) Metrology Interoperability project team; NIST then continued this discussion in 2006 (NIST 2006). These meetings resulted in dividing the metrology system into four main stages that need to be integrated. These phases are product definition, measurement process definition (planning and programming), measurement execution and measurement analysis. Figure 1-4 shows these four measurement stages as well as an exploration of some applied commercial systems. This variety in measurement commercial application, illustrated in Figure 1-4, stressed on the measurement interoperability requirement that is hindered by proprietary software data formats (Brecher *et al.* 2006).

Based on this brief system understanding, integration requirements have been identified at three different data communication interfaces as follows:

1. Design and measurement planning interface, through which the measurement input in the form of tolerances and their related geometries, should be provided manually or through the interaction with the CAD systems. In fact, it could be argued that there is a CAM-measurement interface as measurement data could be obtained using manufacturing features and tolerance information. Inter-feature relations among various CAx systems are discussed in section 5.2.

2. Measurement planning and execution interface, through which a measurement program that represents the measurement process definition is transferred to a particular measurement machine for execution. This research recognises that the measurement planning and execution interface is a misleading one as it

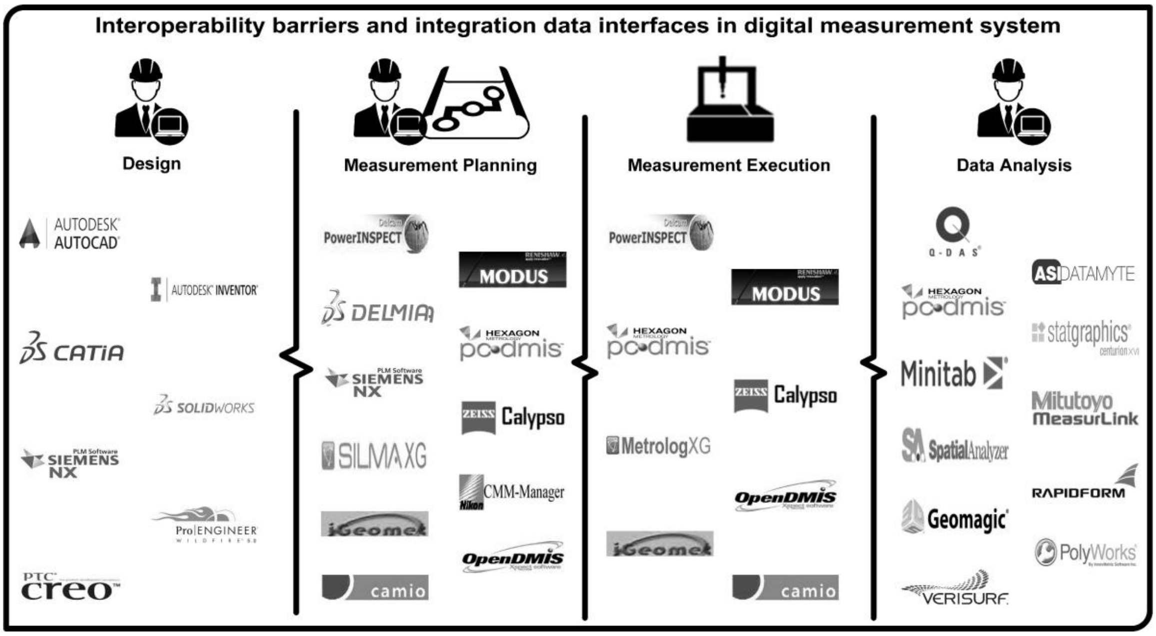


Figure 1-4: Process stages in measurement systems and interoperability barriers

includes implicitly two distinct interfaces that need to be separated to establish the interoperability of the measurement process definition. This research proposes a modified measurement system that defines a new distinct data-connecting interface between the measurement process definition and the programming activities. The defined new interface enables the formulation of resource independent measurement specifications (REIMS) which is the proposed theoretical framework of this research. The REIMS concept is discussed in section 5.2.

3. Measurement execution and analysis-reporting interface, through which the measurement result is transferred for being analysed to infer the required knowledge arising from the measurement process. Following the measurement analysis, the necessary outputs are reported in a form that could be interpreted by the operator or the computerised system to assist in future decision making.

Interfaces between the measurement analysis and other activities such as machining and quality departments are also significant. The measurement results and machining planning integration has been investigated to allow for an adaptive process planning philosophy; this is visited during the literature survey in subsection 3.2.3.

1.3. Thesis structure and organisation

The thesis is organised into nine chapters as seen in Figure 1-5. Chapter 2 follows this introduction chapter by stating the research aims, objectives and the applied research methods. In the following background section, a review of the available literature on tolerance modelling and measurement systems integration is presented in chapter 3. Chapter 4 then portrays the state-of-the-art in the standardisation process that is related to the research scope. The background section of the thesis is then followed

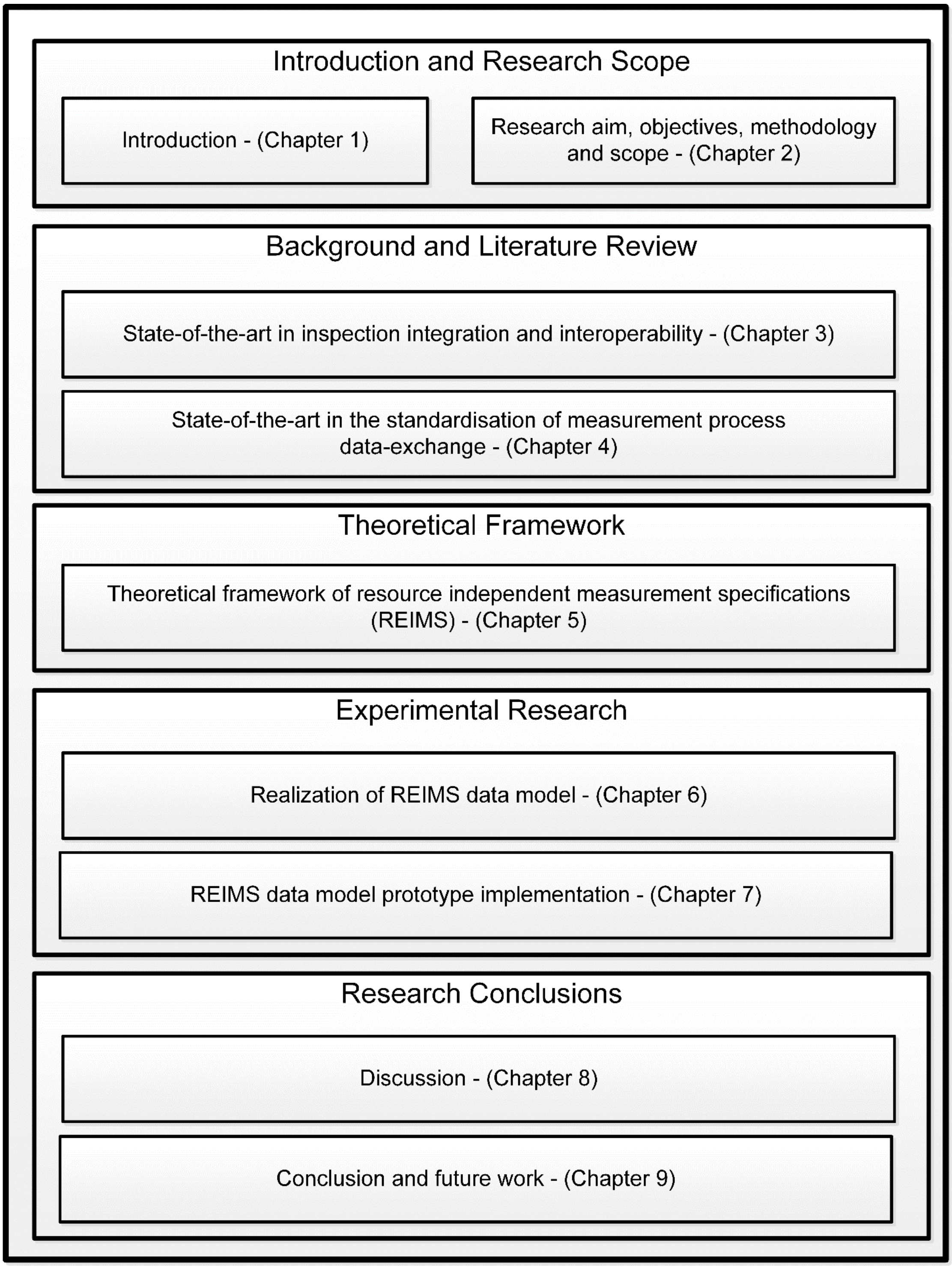


Figure 1-5: Thesis structure and organisation

by the theoretical phase of the research in chapter 5 where the identified gaps in research done by academic and standard communities are summarised and a novel framework to achieve the research aims and objectives is specified. In the experimentation phase, the designed framework is realised, and a prototype system is implemented in chapter 6. This prototype system is then demonstrated and evaluated in chapter 7. The thesis then ends by discussing the implementation results in chapter 8 followed by stating the research conclusions and future work in chapter 9.

2. Research aim, objectives, methodology and scope

This chapter commences in section 2.1 by defining the research problem, stating the research hypothesis and identifying the research aim. In section 2.2, the applied research methods and methodologies are discussed. In section 2.3, the research objectives to achieve the research aim are stated. At the end of chapter 2, the research scope specifies the boundaries of this research to clarify related issues to the stated research aim and objectives, and ultimately to unambiguously define the overall research context.

2.1. Research aim and hypothesis

This research aims to specify, design and realise a resource independent but technology specific framework for defining measurement processes, which allow for interoperable measurement integration with other product lifecycle tasks and various CAx applications. Based on the introduced measurement system analysis in section 1.2, this work is related to three main issues that are challenging the formulation and exchange of measurement plans. The seamless exchange of a clearly defined measurement process enhances the consistency of measurement results, which reduces the overall measurement process uncertainty. These problems can be described as follows:

1. The lack of an interoperable and standardised framework for enabling the exchange of measurement process definitions due to the implicit link between the measurement planning and programming tasks, as the latter is highly dependent on pre-specified measurement equipment. As has been depicted in Figure 1-4, both of the measurement planning and the measurement execution tasks are mostly achieved through the aid of the same proprietary systems, which directs the control of a specific measurement equipment. A standard and resource independent framework for representing the measurement process endeavours to achieve interoperability among those proprietary formats of measurement plans and systems.

2. The absence of an unambiguous integration framework that includes the complete data required for the definition of the measurement process while taking into consideration the manufacturing context. Considering the manufacturing information such as machining features and operations during the definition of the measurement process is crucial to establish the appropriate data

connection between the gained measurement knowledge about both products and processes and the related technical data and parameters. Considering the manufacturing context enables manufacturing system control by closing the loop of both design and machining stages as depicted in Figure 1-2.

3. The variability in the quality of the gained measurement knowledge due to operator-dependent decisions taken during the planning stage, especially during the definition of the applied data analysis tools for processing the measurement extracted data from the physical part surfaces in addition to the definition of the extraction parameters itself. This deficiency is mainly due to the absence of measurement good practise guides and standards.

The research hypothesis can be stated, as the formulation of an interoperable definition of measurement process would enable the reduction of variability in gained measurement knowledge, which is due to operator-dependent measurement planning occurred before both measurement programming and execution stages.

The proposed formulation introduces the concept of REIMS, which is based on a proposed modified flow of data within the metrology system. The proposed modified measurement system separates the measurement programming and measurement equipment selection tasks from the definition of the measurement process. The proposed framework provides the necessary information about the measurement process requirements in the modified data flow of the measurement system. These measurement requirements could be then compared to individual measurement device capability profile to assist the measurement equipment selection task.

This work also conceptualises design and implements an information modelling framework for representing REIMS for the coordinate measurement of prismatic parts. The purpose of the modelling framework is to provide a means for exchanging the data included in the measurement process definition as an explicit and clear instruction to direct subsequent measurement activities. A significant interoperability and flexibility barrier in the measurement system will thus be removed by using the proposed modelling framework.

2.2. Methods and methodologies

The research hypothesis was introduced in section 2.1 to address a defined problem within the digital measurement system. Consequently, this investigation will follow the deductive scientific research methodology. In this research methodology, a proposed hypothesis is defined to solve an identified problem from the existing literature followed by the testing of the proposed hypothesis to prove or disapprove it (Bryman and Bell 2015; Greener 2008). In addition, this research is implementing the designed framework in the form of a software prototype. Constructing such a software prototype is considered as a building research methodology among those used within the computer science field. This methodology aims to prove the possibility to build a physical or software systems and models to solve a particular problem (Elio *et al.* 2011; Kasanen *et al.* 1993).

System Engineering methods and tools are necessary for the development of a software prototype for performing specific functions within a defined system. System engineering methods are seen as a mapping tool between system requirements and structured system description (Lightsey 2001). This research deploys system engineering approaches to analyse the requirements, functions, inputs, outputs and constraints of the proposed information modelling framework. These approaches start by listing high-level requirements of the system and deriving detailed requirements. The requirements are then mapped to functionalities that the system must provide. Tools such as IDEF0 are used at this stage to decompose high-level functions into low-level functions. The system analysis will be based on the concepts and knowledge presented in official standards, best practice guides and commercial measurement software documentation.

Standard documents will establish the limits of the applied knowledge within this work as standards represent the knowledge that has been agreed nationally or globally for industrial practice. In addition, expert technical committees and academics review routinely standard documents, which increase the confidence in these sources of data. Based on the analysis of the outcomes at the end of this stage, the proposed design of the system's functional components will be presented in the form of information models using STEP methods such as EXPRESS-G tools. The internationally accepted open industrial standards, such as STEP, will be the basis for the implementation of the designed information model; this is to ensure interoperability and applicability of designed system within an industrial environment. At the final research stage, a sample test piece is selected to test the abilities and limitations of the designed framework. The selected test case includes prismatic features that are augmented by different design specifications. The test pieces are exported from a CAD system in the form of a STEP-based part 21 file to evaluate the ability to use the design information directly within the proposed framework without unnecessary translation or modification steps. CTC-01 test case provided by NIST, in the form of STEP AP242 file, for testing the interoperable exchange of design specifications between different CAD systems is selected for this work. STEP AP242 is an authority model that satisfies the necessary requirements of model-based definition (MBD) and this research.

The author supports the view that modelling tools and languages should be used in a complementary rather than a competitive manner (Peak *et al.* 2005; Kim *et al.* 2003). Consequently, this research strictly adheres to the modelling tools and language applied within the STEP world to ensure interoperability of the proposed framework. In addition, The EXPRESS modelling language for STEP is a powerful tool that enables the coding of different rules and circumstances that are applied to the modelled data requirements. EXPRESS is also implementation independent, for example, EXPRESS-based data can be exported as text-based or XML-based files; the latter makes it suitable for web exchange applications.

2.3. Objectives

Based on the methodology detailed in section 2.2, the following objectives have been identified to underpin the various stages of work required to achieve the research aim:

1. A comprehensive review of tolerance modelling, measurement planning and measurement integration research to identify the interface that connects the design and verification phases, and also the interface that connects the measurement planning and measurement execution stages.

2. The evaluation of the currently applied data models, where they exist, at identified interfaces in the objective number 1, with particular attention to the state-of-the-art standardised data models.

3. The evaluation of the recent tolerancing standards and practices, which includes the definition of “what is to be measured?” and “how it is represented?” these include:

   - Standardised practice of geometric and dimensional tolerancing in documents such as ISO 1101 (ISO 2012b) standard and the American society of mechanical engineer ASME Y14.5 (ASME 2009) standard.

   - Standardised concepts of the presentation and representation of the 3D CAD models digitally in both ASME Y14.41 (ASME 2012) and ISO/DIS 16792 (ISO/DIS 2012) standards.

- Standardised data exchange mechanisms for exchanging geometrical and tolerance information in the standard for the exchange of product model data (STEP) documents, for example, STEP-AP242 (2014).
- The modern definitions of features and characteristics in the next generation of geometric product specifications for both design and verification, which is presented by ISO/TC213 as an ISO GPS standard series. These standards are introduced in ISO 17450-1 (ISO 2011h) and ISO 17450-2 (ISO 2012c).

4. The identification of the necessary requirements for representing measurement operations. These requirements can be defined through investigating measurement best-practice knowledge and the measurement planning and programming standards or documentations that include:
5. The evaluation of the current measurement standards such as ISO STEP AP 219, STEP-NC part 16, The dimensional measurement interface standard (DMIS) and The quality information framework (QIF) to identify their scope, strength and limitations.
6. The identification of the necessary modifications to the current measurement system structure and measurement data models to cope with modern digital manufacturing and interoperability needs.
7. The specification of necessary requirements for the design of the REIMS framework.
8. The design of the information modelling framework for the REIMS system.
9. Development of an experimental platform for a prototype implementation of the realised framework. The experimental platform includes the selection of appropriate industrial test cases for testing and evaluating the capabilities and the limitations of the proposed software prototype.

2.4. Scope and boundaries

This research spans across different domains, as can be seen in Figure 2-1. The research is concerned with the design and measurement activities among other activities involved within the PLM chain such as machining and assembly. Within the design stage, the conversion of functional requirements into design specifications and the degree of correlation between them are considered to be out of scope. The reason for this is that

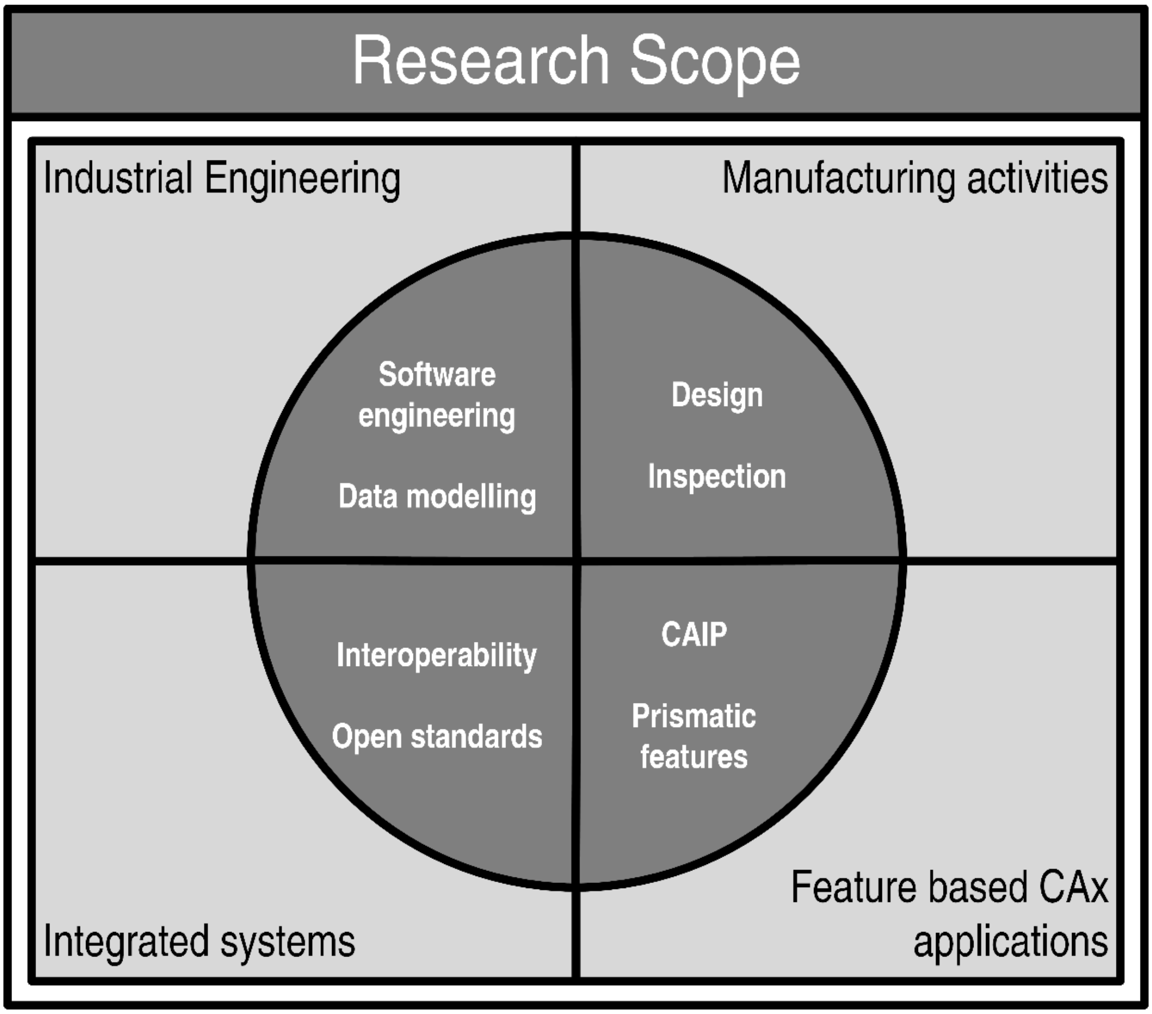


Figure 2-1: Research scope and boundaries

these activities do not affect the definition or the execution of the measurement process. In addition, it is the sole responsibility of the designer to define complete and correlate specifications. Functional requirements include ensuring correct assembly, applying a controlled wear or lubrication characteristic, desired strength or interaction in a specific manner with an electromagnetic wave or fluid in aerodynamic and optical applications. Methods for converting functional requirements into design specification were reviewed by Elmaraghy *et al.* (2013). Throughout this work, it will be assumed that the published characteristics from the design stage are correctly correlated to the functional requirements and are complete; this assumption means zero correlation uncertainty, as defined in ISO 17450-2 (ISO 2012c). Conversely, only the output design characteristics from the design stage are within the scope of the definition of the measurement process as it is used during the definition of the part geometric entities to be measured.

Concerning measurement, the execution and the statistical analysis of aggregated measurement results over time are not part of this research. This exclusion breaks the link between the measurement process definition and a specific execution method. Likewise, the exploration of how the machining and assembly function can be controlled using the measurement results is not part of the research objectives, but creating the necessary data requirements for enabling this control functionality is included. This investigation focuses only on the CAI systems among CAx applications for defining the measurement process of prismatic features. It is assumed that the features are already available in computer readable format, and therefore, feature recognition is considered to be outside the scope of the work.

In addition, from the view of manufacturing research, Figure 2-1 shows that this research lies within the context of industrial research that applies mathematical and computer science concepts to enhance the manufacturing systems performance. This research will deploy data modelling techniques from both computer science and system engineering to achieve the intended integration and data exchange. To ensure interoperability, the proposed model will use open standards as its base technology, as standardisation is accepted as an interoperability enabler (Morse *et al.* 2016). The developed model in this research can assist the selection of measurement equipment by providing necessary accuracy, uncertainty and size requirements for measurement tasks. However, this does not include modelling of the measurement equipment as the research is based on the resource independence philosophy. Resource independence principle also excludes measurement system design, measurement uncertainty estimation or traceability from the research scope. The interaction of the developed system with inspection planning algorithms shall be discussed without detailed illustration of the used algorithms as these algorithms have already been covered as will be shown in the literature review in section 3.2.

3. State-of-the-art in inspection integration and interoperability

This chapter reviews the state of the art developments in areas related to the defined research scope as described in chapter 2. This chapter commences in section 3.1 by describing the natural data input that guides the computer-aided inspection planning (CAIP) task at the design and measurement tasks' connecting interface. This section covers the efforts done toward the establishment of model based definition (MBD), which is necessary for digital manufacturing and the support for downstream applications. Section 3.2 covers the measurement planning and integration research. This chapter targets the identification of the necessary data elements required for guiding the measurement task up to the execution phase. Moreover, it leads to the conceptualisation of the CAIP framework followed by the necessary discussions in section 3.3 to identify the research gaps and further needs to be developed.

3.1. Model based definition (MBD) and geometric product specifications (GPS)

3.1.1. Model Based definition and the product manufacturing information (PMI) representation

Measurement planning integrity is influenced directly by its data communication interface to the product design phase. The quality of a measurement plan is based on amount, type and quality of the information provided from the product definition phase. Today this data exists in the form of a drawing sheet or a solid model. Although the benefits of the solid modelling principle are directed towards the overall goal of digital manufacturing, there are still issues that hinder its full applicability. Manual intervention is still necessary during downstream applications to perform manufacturing and measurement tasks (Fischer *et al.* 2015). In addition, despite being in the digital manufacturing era, the supply chain still receives designs as fully detailed 2D drawing sheets or a geometry-based solid model accompanied with 2D drawing to show the PMI data (Anwer *et al.* 2014; Hartman *et al.* 2012).

This current nature of the supply chain affects the efficiency of the downstream applications and increases the time frame to accomplish the required tasks. Issues such as incompleteness of the published designs as 2D drawings may be discovered later in the downstream stage, also remodelling or manual insertion of the PMI data may be necessary. Researchers have attempted to use open standards to integrate measurement tasks with CAD or CAM databases, to evaluate the possibility of driving an automated measurement application.

For example, Haibin Zhao *et al.* (2006) and Barreiro *et al.* (2003b) integrated measurement with a design model to obtain feature information through the internal API functions of a specific CAD/CAM system. Figure 3-1 illustrates the inspection framework for concurrent information access (IFCIA) system presented by Barreiro *et al.* (2003b) that included a functional module produced using CATIA's API functions to interact with CAD system information and to define a structure for managing the 13 data groups shown in Figure 3-25. IFCIA also included a user interface module to enable the input and the storage of data defined in the created data model by Barreiro *et al.* (2003b) into a central database.

Haibin Zhao *et al.* (2006) and Imkamp (2005) extended this by writing and manually linking STEP and Q-DAS (Q-DAS 2008), to associate tolerance data in the Q-DAS file with related geometries defined within STEP data. Q-DAS data format is used for the analysis and management of measurement data as it includes definitions for representing tolerances in its framework. Figure 3-2 illustrates how the inspection plan and measurement run used the shape and tolerance data distributed in Q-DAS and STEP files.

Even tolerances have started to be introduced within STEP, Sathi and Rao (2009) evaluated the integration with the CAD system through STEP files augmented by tolerance information. Although, it was concluded that the information in the STEP file was not available in the suitable format required by inspection applications, and thus,

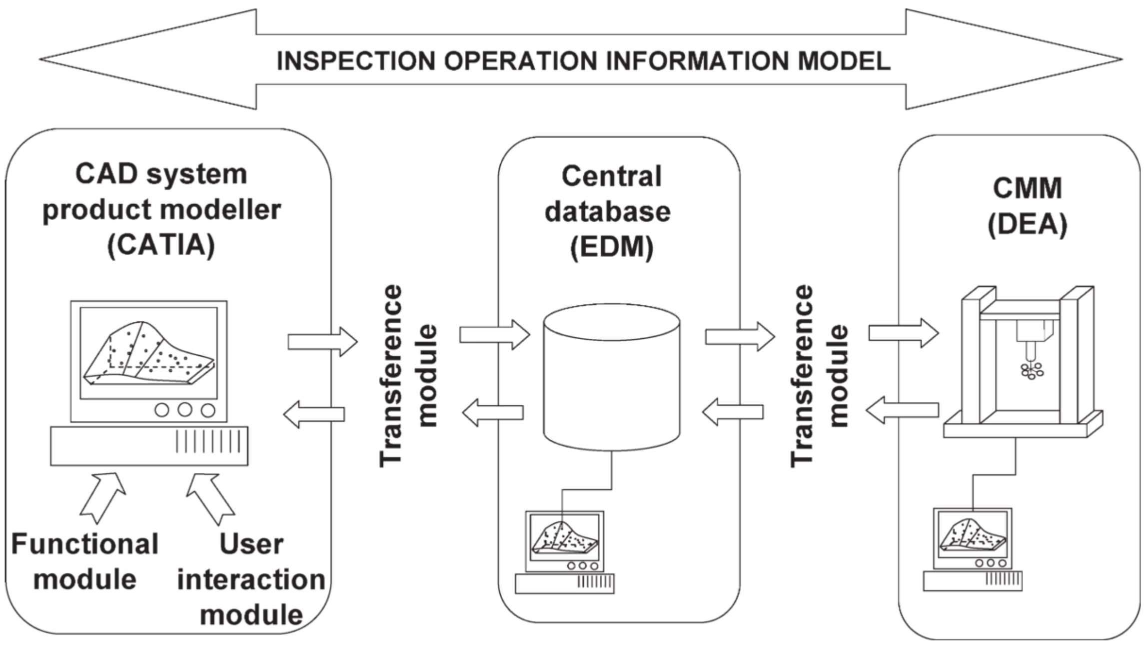


Figure 3-1: IFCIA framework (Barreiro *et al.* 2003b)

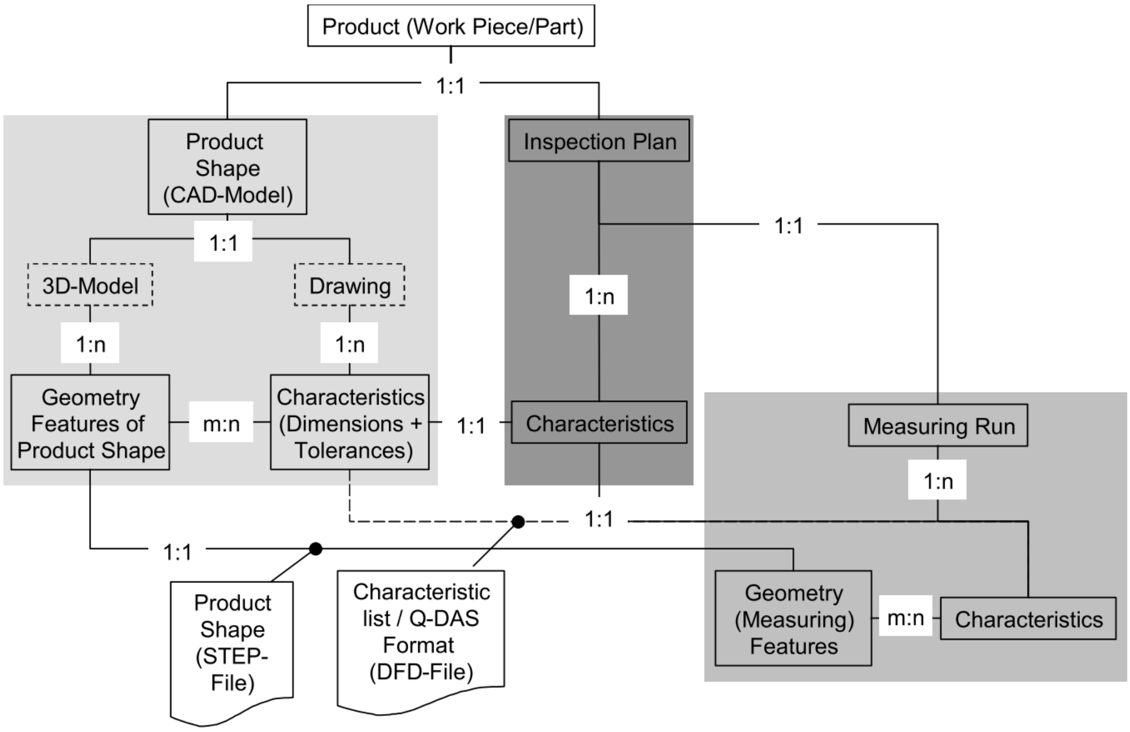


Figure 3-2: Transfer of inspection data from CAD database (Imkamp 2005)

validation and synthesis steps were necessary. To summarise, the integration between the measurement processes and the design phase was hindered by the lack of necessary information provided by the CAD data, while the same issue impeded the automation from one side, the lack of standardised measurement practice challenged the automation from the other side. These obstacles indicated that measurement systems still lack the required automation objectives.

The industrial goal today is to achieve a model based engineering (MBE) vision. MBE strategy is based, at its core, on the MBD, which implies the creation of a digitally complete product definition. MBD is the solid model augmented by the PMI and the necessary semantics; this applies for both parts and assemblies. Figure 3-3 clarifies the concept of the MBD as a combination of the 3D representation completed by the associated data. The strategy enables the product lifecycle to become model-centric, which reduces time, costs and errors (Fischer *et al.* 2015). Quintana *et al.* (2010) agreed that faster and possibly more accurate measurement processes would be achievable through adopting the MBD formats within industry.

Zhao *et al.* (2011a) reported that solid models were initially developed using the constructive solid geometry (CSG) representation or the boundary representation (B-rep). Today’s CAD environments use the B-rep with a history tree, which allows model

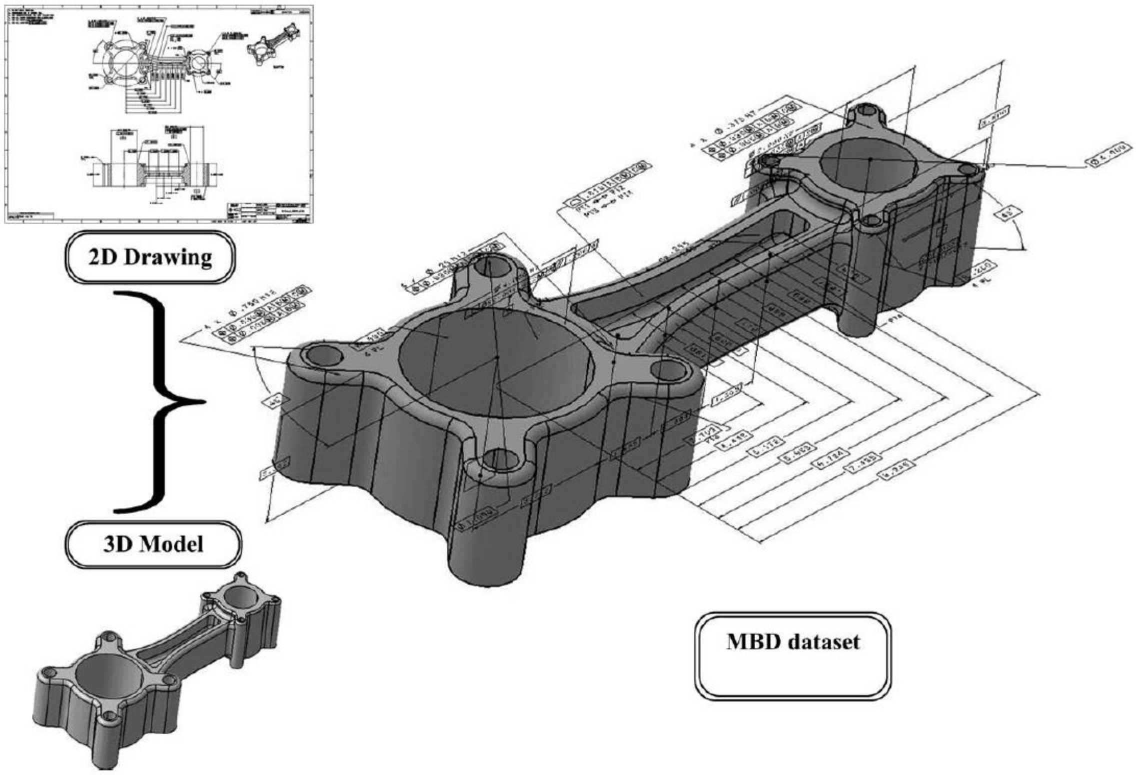


Figure 3-3: Model based definition for digital manufacturing (Quintana *et al.* 2010)

modifications by rolling back through the modelled data (Shen *et al.* 2008). CAD databases include all the geometrical and topological data necessary for representing the nominal product boundaries. The designers must specify the permitted variations of the nominal part boundary and the geometric constraints between its geometric entities. These variations are specified to accommodate manufacturing and measurement errors while not sacrificing the targeted functional performance. The first national drafting standards to emerge were the British Standard issued in 1927 and the American Standard for drafting released in 1935 (Srinivasan 2008). ISO 1101:2013 (ISO 2012b) and ASME Y14.5:2009 (ASME 2009) are the latest applied standardised practise for using the design specifications' syntax. Over the years, these standards have tried to harmonise the visual representation of the required specifications of a product.

The derived semantics are defined through the GD&T rules represented by different documented examples and figures, which is a human understandable format rather than being computer interpretable. As a result, computer readable tolerance modelling has gained the interest of many researchers over recent years. In fact, the majority of GD&T representations have been studied to fulfil the tolerance analysis needs (Shen *et al.* 2008), which consider the representation of the aggregated variations in parts and assemblies. These frameworks aimed to provide the designer with computerised tools to assist tolerance synthesis, specification, validation and analysis tasks (Dantan *et al.* 2008; Salomons *et al.* 1993). These tools are known as the computer-aided tolerancing (CAT) applications that enable the management of the geometric variations (Anwer *et al.* 2014). Tolerance boundaries were first represented by the offsetting operations and the variational class theory by Requicha (1983). Tolerances were implemented based on this theory as attributes of a variational graph linked to a CSG solid modelling system (Requicha and Chan 1986). Offset method is a limited representation, for example, it is not suitable for representing the floating tolerance zones; it also insufficient when dealing with singularities (Kethara Pasupathy *et al.* 2003). Johnson (1985) stored the tolerance data with the B-rep solid models while Wang and Ozsoy (1991) and Roy and Liu (1993) attached it with a hybrid CSG/B-rep representations.

Later, the tolerance data was represented in an explicit manner as constraint nodes attached to the model faces (Roy and Liu 1993). An early objective of tolerance models was to store the tolerance information within the model database for basic modification or retrieval needs. In their survey, Kethara Pasupathy *et al.* (2003) reviewed the methods used to construct the tolerance zones for the tolerance analysis purposes. This work compared the different methods according to the range of features applicability, suitability for dealing with singularities and manufacturing fields of applications. Offset, parametric, algebraic, homogeneous transformation and user defined tolerance zones were those included in Pasupathy et al.'s review. For supporting the tolerance synthesis and validation tasks, Wu *et al.* (2003) developed a directed attributed constraint graph representation, in which, tolerances have been applied as constraints on the metric relationships between different entities. Figure 3-4 shows an example of a subgraph representing the orientation tolerances as a constraints node attached to the metric relationship between geometric entities. It is worth noting that these attributed tolerance representations are not suitable for automating the tolerance analysis

(a) Parallel relation and its parallelism tolerance

(b) Perpendicular relation and its perpendicularity tolerance

Figure 3-4: Tolerances as constraints between geometric entities (Wu *et al.* 2003) applications (Shen *et al.* 2008). Shah *et al.* (1998) used the dimensional graph structure to represent the GD&T data. This model was based on the relative degrees of freedom (DoF) among the different geometric primitives. Based on the same concepts, Shen *et al.* (2008) used a separate super-constraint-tolerance-feature graph (SCTF-graph) model for automating tolerance analysis process. The graph model includes nominal geometry, constraints, tolerances, DoF(s) to be controlled, assembly hierarchy, and their respective inter-relationships. They represented nominal information using trimmed features which is an approximated abstracted forms that are suitable for tolerance analysis purpose but not for measurement applications. Figure 3-5 depict an example of the constrained graph model used to represent relations between features and tolerances.

The surveyed tolerance modelling literature showed that the academic research focused mainly on the ASME Y14.5 early versions, which have been recently modified to remove further ambiguity in its specifications and their interpretation. In addition, the tolerance models aimed to provide sufficient information to be utilised by the subsequent

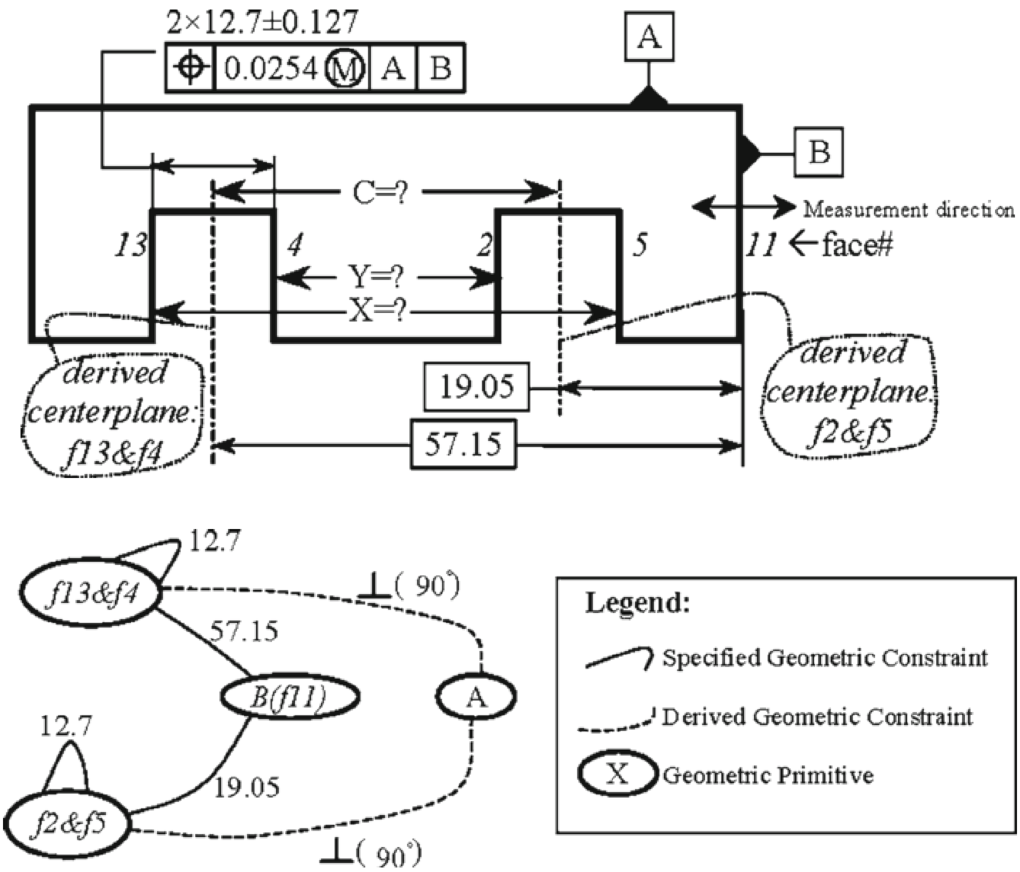


Figure 3-5: An example of the constrained graph developed by Shen *et al.* (2008)

machining and assembly stages. Consequently, current CAD information is still unable to support CAI integration effectively (Lemu 2014), which is a requirement for establishing the digital manufacturing vision (Majstorovic *et al.* 2014). It was noted that few researchers have been concerned with studying the tolerance models from the measurement perspective.

Xiaoping Zhao *et al.* (2006) have attempted to fill this gap by merging the already existing tolerance definitions from ASME Y14.5-1994, STEP and DMIS standards. The merged framework was designed in a layered structure without modifying the included data definitions or requirements, which did not solve the same issues raised by the current tolerance models. Figure 3-6 shows one Express-G diagram of the developed layered model to represent geometric characteristics where the different colours represent the different model layers.

Recently, standard organisations began to update the tolerance knowledge and use to remove any ambiguity in the geometric specifications; one example of these modifications is the additional modifiers introduced in ASME Y14.5 (ASME 2009) to present view dependent tolerances and to define datum boundaries. The development of an open standard for representing the tolerance data systems has been another concern for the standards organisations. Open standards aimed to enable the tolerance data exchange among different CAD systems. The author has recognised that based on the academic research the standard organisations were the major contributors in the latest advances in tolerance modelling and representation. Standards' developments for augmenting the solid model with the tolerance information will be illustrated through the detailed discussions of the STEP standardised documents in subsection 4.1.5.

3.1.2. Geometric product specifications (GPS) origin and research

Subsection 3.1.1 discussed the challenges related to the formation of a widely accepted and unambiguous method to specify design data, which could be easily consumed by downstream systems. New challenges emerged with the emergence of the coordinate metrology tools; variabilities between the standard definitions and the applied coordinate metrology methods increased the overall process uncertainty. This problem has been realised as the coordinate measurement systems began to replace traditional measurement instruments, as many specification standards were based on the principles of the conventional measurement techniques. Furthermore, the metrologists always think about aspects that the designer has not considered (Ballu *et al.* 2015), these aspects are related to measurement data collection and analysis decisions to cope with

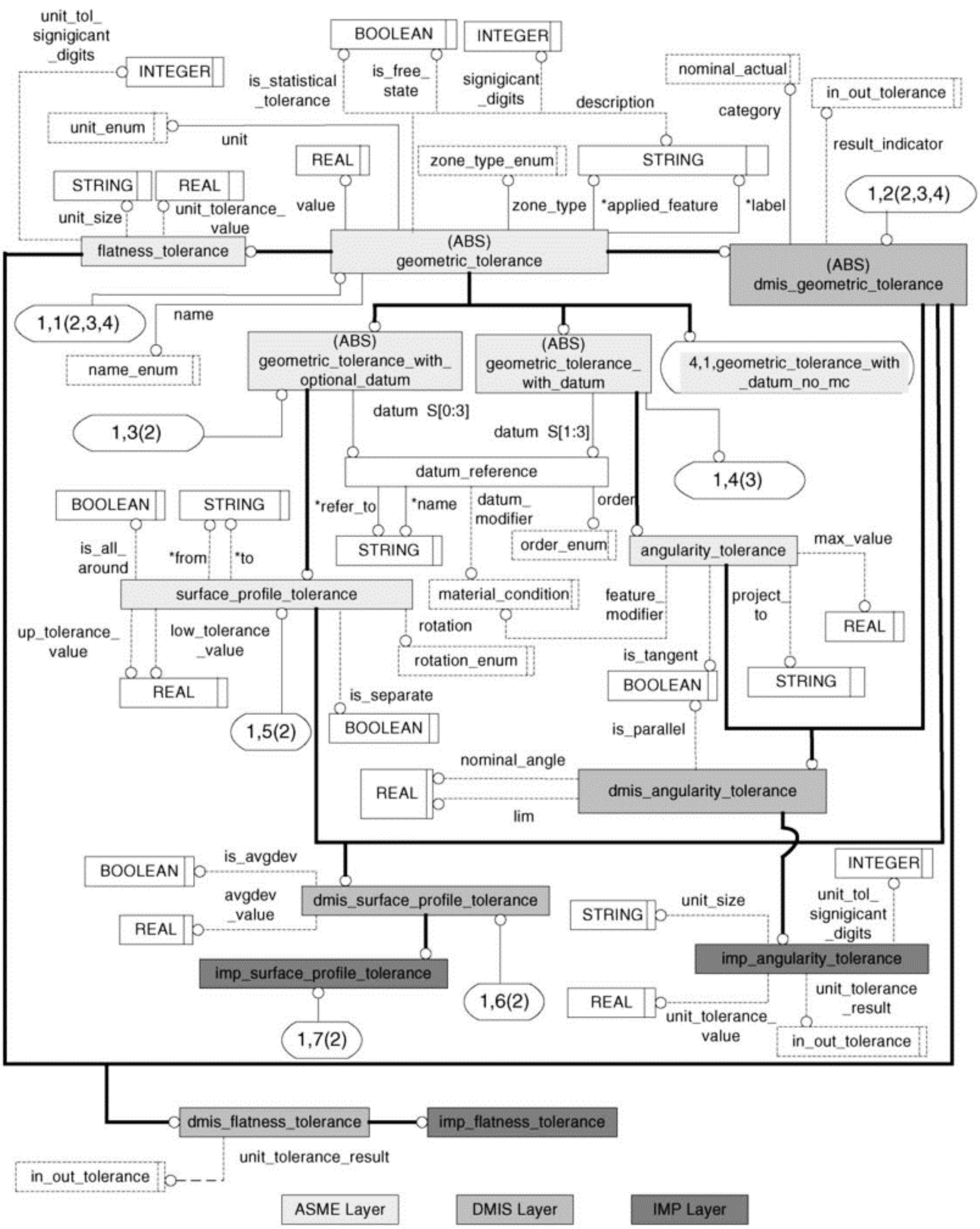


Figure 3-6: Layered representation of geometric tolerances (Xiaoping Zhao *et al.* 2006)

standardised specification definitions. Reducing such uncertainty sources through the product lifecycle was a major concern that led to the development of the combined uncertainty concept within the ISO GPS framework.

Researchers in computational metrology evaluated the conformance of the applied tools for measurement data analysis with the standardised specifications; these efforts could be grouped under the title of metrology software testing and evaluation (Diaz and Hopp 1995; Carr and Ferreira 1995b, a; Ballu *et al.* 1991; Weckenmann and Heinrichowski 1985). Software testing evaluating the conformance of the applied measurement analysis algorithms to reference algorithms at standard organisations to reduce uncertainties related to the used measurement software. In addition, some work investigated the effect of the workpiece errors itself on the final analysis results, as well as, the effect of measurement errors on the fitting routines (Forbes 2013; Forbes 2006).

To illustrate, one early computational metrology research outcome was to consider the least square (LS) fitting method as only an approximation for easing the mathematical manipulation of the metrological tasks (Ballu *et al.* 1991). As LS was applied as the default method in measurement software, the need for the definitions of another fitting criterion started to emerge to match more precisely the standard definitions and functional requirements.

Vemulapalli *et al.* (2013) concluded that the differences between measurement results between different coordinate measuring machines (CMM) are mainly due to two reasons. The first is related to software uncertainty, which means the degree of conformance of the applied algorithms in a specific software to those reference algorithms at standard organisations. The second is due to the incorrect match between the applied analysis algorithms with the tolerance data. The NIST software conformance testing solved the first issue, and hence Vemulapalli *et al.* (2013) tried to find normative analysis choices that match the manual inspection methods or the standard tolerance definitions. The definition of new analysis tools was not the only concern, the lack of standardised format on how to apply or use them to match the design specification was also an issue. In this context, Mani *et al.* (2011) proposed an approach to standardise the applied fitting methods by taking into consideration the standardised specification definitions. These studies raised the awareness of the need for a measurement practise standards to assist measurement process planning and definition stage.

Although these efforts tried to map the designed specifications to the measurement analysis tools accurately, the unambiguity of the specification itself remained an unresolved issue. As a way to solve these challenging topics between specification and measurement, the GeoSpelling concept was introduced by Ballu and Mathieu (1996). GeoSpelling was proposed to ISO for rebuilding of standards for the tolerancing and metrology fields (Dantan *et al.* 2008), in what is known today as the ISO GPS standards series. GeoSpelling was initially based on the analysis of the geometric specification standards and the study of the computational measurement analysis tools existing at the time of its initial conceptualisation. The GeoSpelling approach aimed to formalise a universal language to state unified expressions for the geometric specifications. These expressions enable the semantics of specifications to be communicated to define their meaning clearly (Ballu *et al.* 2015).

Mathematical expressions could be directly derived based on the GeoSpelling language to represent the technical problem uniquely at hand. Mathieu and Ballu (1998) deployed this approach for realising the virtual gauge concept as a measurement software functionality. A complete expression was stated for the virtual gauge specifications, which is then mapped to a mathematical expression of these specifications. Linearisation techniques were applied during the mapping for simplifying the solving process, which was performed by the simplex method. The virtual gauge as a measurement analysis capability was first discussed by Weckenmann *et al.* (1991) and Feng (1991). At this early stage, the GeoSpelling language was not defined, but its initial concepts began to emerge (Mathieu and Ballu 1998). The fundamental concept was that a specification is a condition on a characteristic of a feature, and the geometric feature is derived from the real surface through a set of operations; Figure 3-7 illustrates GeoSpelling basic concept in which a specification is seen as a condition on a characteristic defined from a geometric feature that is obtained through defined operations on the ideal or non-ideal part model.

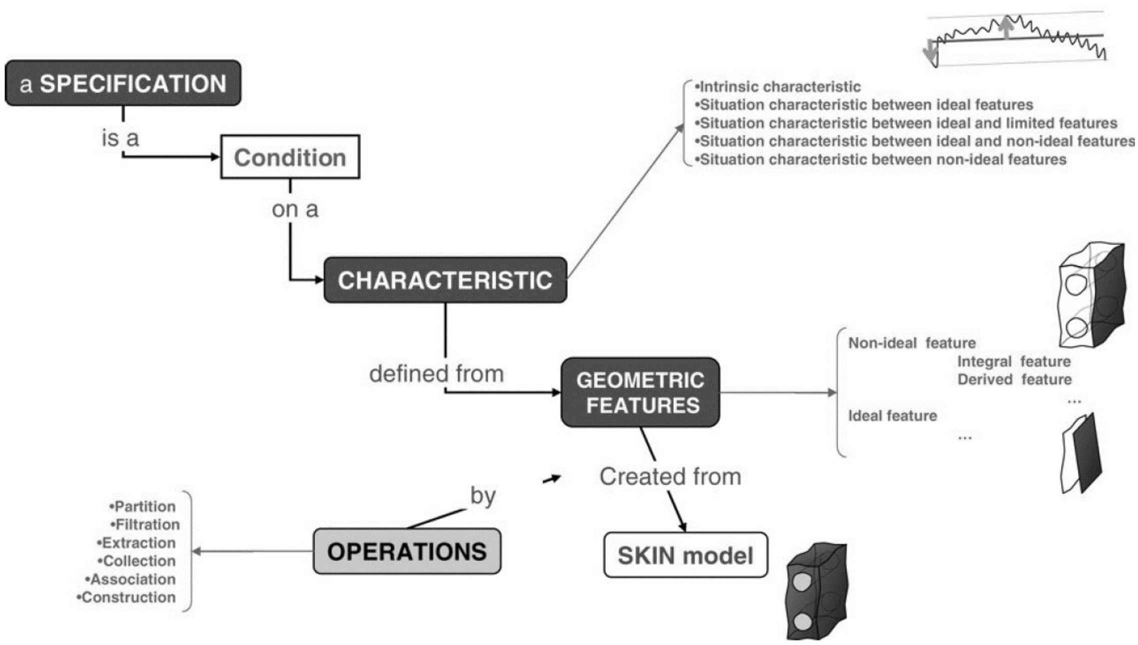


Figure 3-7: Geospelling basic concept (Dantan *et al.* 2008)

The ISO GPS evolving standards and their reflection on the current dimensioning and tolerancing activities were extensively presented and illustrated by Dantan *et al.* (2008), Srinivasan (2013), Nielsen (2013), Morse and Srinivasan (2013) and Srinivasan (2015). In section 4.2 of this thesis, the ISO GPS series structure and its theoretical foundations will be a detailed topic of discussion. Although ISO GPS has a potential in supporting product lifecycle chain, it is worth stressing that these specifications are still formatted in a text-based manner for human understanding, which hinders their potential applicability in digital manufacturing applications that is a current industrial need. In addition, the newest version of the tolerance standards, based on ISO GPS definitions as in the (ISO 2012b), are not yet practically applicable in design stage. **Thus, the theoretical foundation of the ISO GPS standard series should be encoded in a computer interpretable format to enable its exchange and consumption with the downstream application.** Computer readable form of ISO GPS would increase the benefits of its theory and encourage its applicability to support downstream activities. Reducing variability during the measurement planning stage is an example of the potential benefits of the applicability of ISO GPS concepts.

On this basis, researchers have recently started to investigate applying some of the GPS definitions to tackle specific technical problems or to enable the practical realisation of these definitions . Lu *et al.* (2008) proposed a general model to evaluate the compliance uncertainty based on the compound uncertainty GPS principle. Lu *et al.* used a case study to evaluate the uncertainty due to the design specification ambiguity, and hence they were of the opinion that there is a need for completing the design specifications with more elaborate tools to reduce their ambiguity and misinterpretation. Consequently, the VirtualSurf project aimed to achieve a knowledge-based system to assist designers during the surface texture specification. Wang *et al.* (2005), Wang *et al.* (2006) and Lu *et al.* (2006) used the category theory (CT) to model the components of the specifications' callouts of surface texture. In 2010, Lu *et al.* used a cylindrical example to show the capabilities of the proposed categorical data model for representing the cylindricity specification operator with conformance to GPS tools. This effort was similar to the work presented by Qi *et al.* (2010). An example of this specification operator is shown in Figure 3-8 where the specified value is presented with the conditions required for its evaluation such as the used filter, nesting index, fitting method and extraction strategy. Figure 3-9 and Figure 3-10 illustrate the categorical data model developed for representing surface texture specification in a way that is discussed in Figure 3-8.

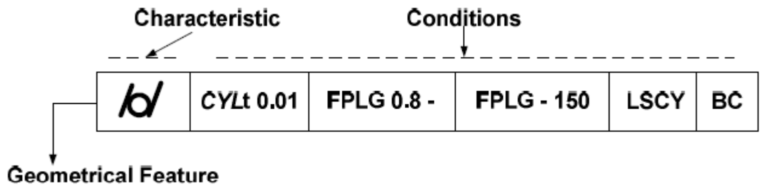


Figure 3-8: Proposed cylindricity GPS-based drawing indication (Lu *et al.* 2010a)

This VirtualSurf project aimed to help the designer in choosing appropriate GPS parameters based on defined functional requirements. This project was completed later by the unified GPS knowledge acquisition and representation retrieval mechanisms demonstrated by Xu *et al.* (2011). Ballu *et al.* (2015) argued that GeoSpelling still lacks a complete syntax for it to be completely unambiguous. Therefore, they proposed a syntax similar to those used in a procedural programming language to reduce further ambiguity in GeoSpelling specifications. Figure 3-11 shows an example of their illustration of the GPS-based perpendicularity specification using a procedural programming syntax.

It is worth mentioning that, Ballu *et al.* (2015) supported the view that applying GeoSpelling should go beyond the simple expression of the design specifications, and

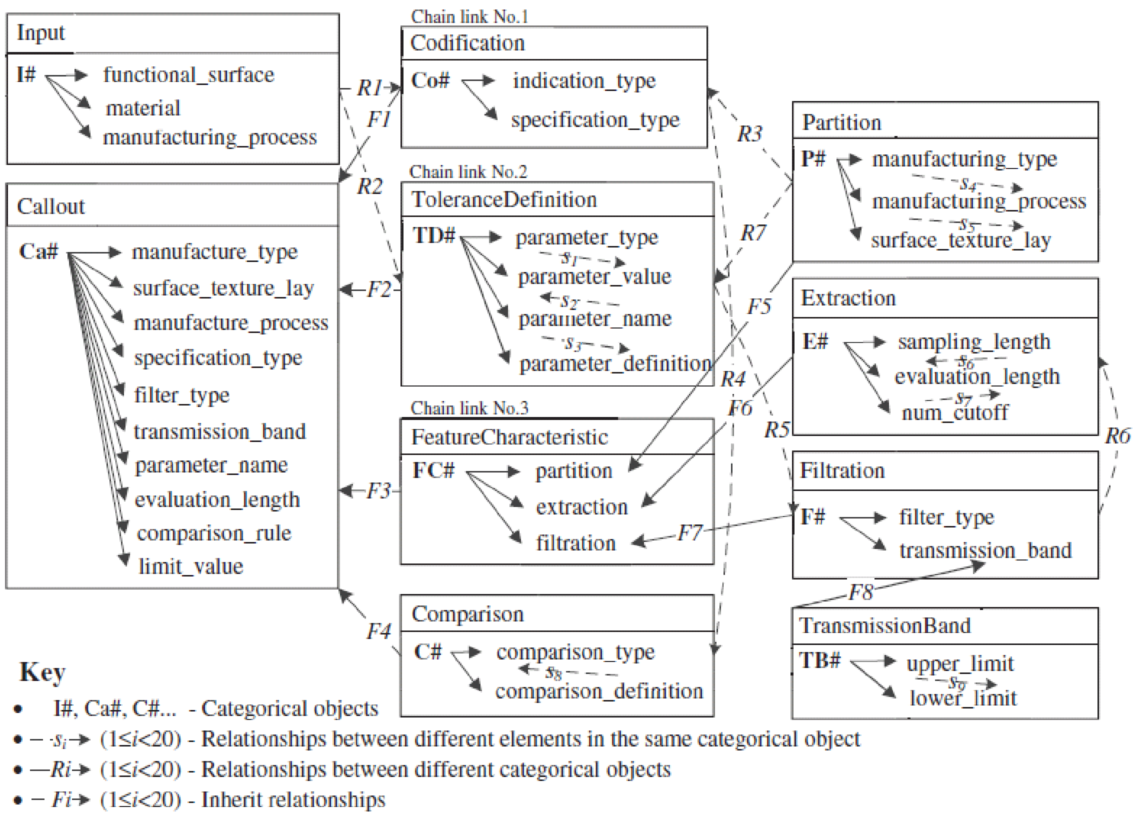


Figure 3-9: Categorical data model for surface texture specification (Qi *et al.* 2010)

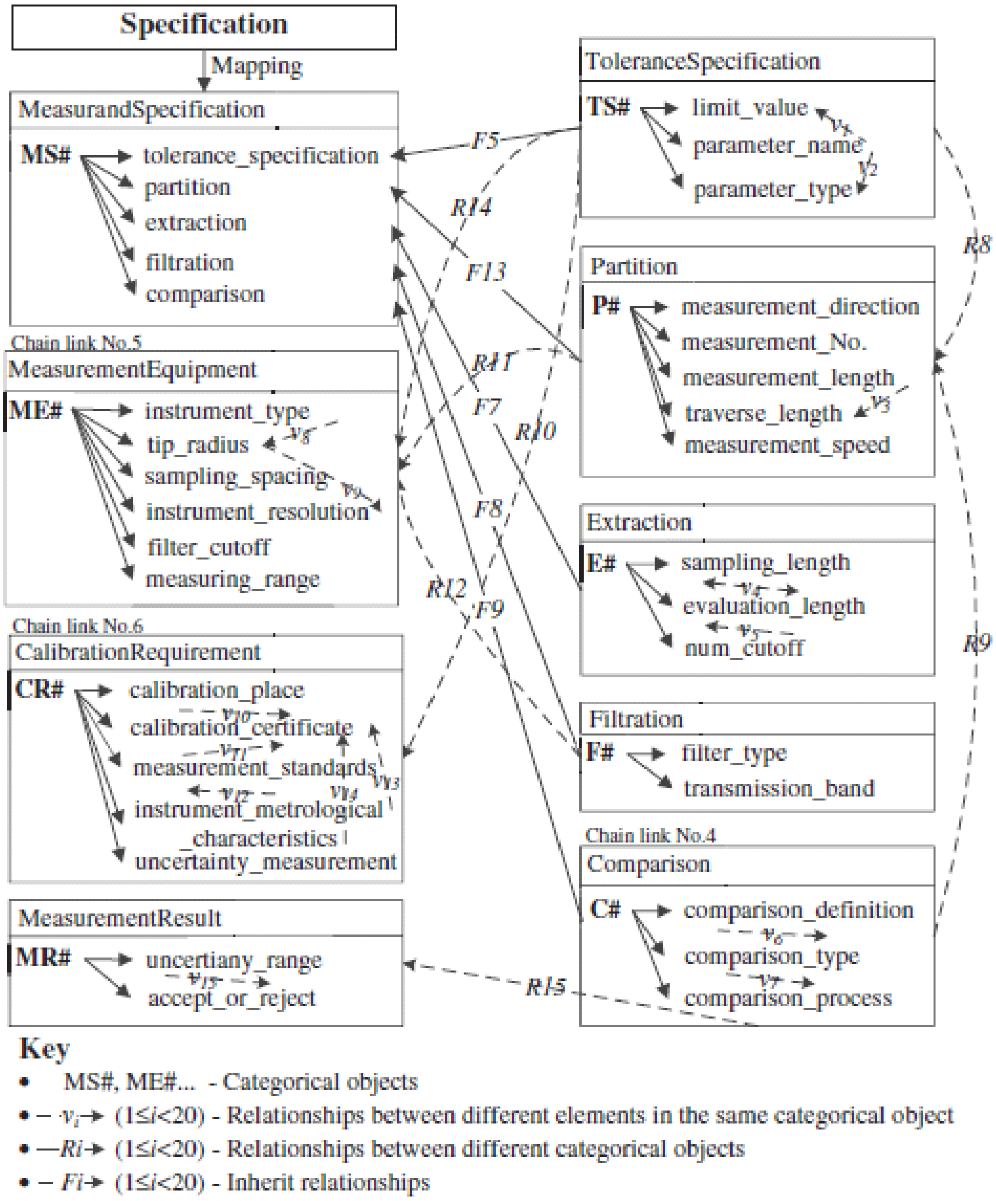


Figure 3-10: Categorical data model for surface texture verification (Qi *et al.* 2010)

that there are possibilities for using GeoSpelling in future research to simulate metrology, assembly or manufacturing. This thesis adds the possibilities to benefit from GeoSpelling principles to enable data exchange and measurement integration objectives. Furthermore, Qi *et al.* (2013) and Dantan *et al.* (2008) agreed that design engineers are still employing old versions of specifications standards; probably as they are simple and save space in the drawing. On this basis, Qi et al. (2013) proposed the use of the default values and simple CAD symbols that are accommodated by some attributed data to simplify the GPS specifications.

```
%SM1: Skin model of the part
%NM1: Nominal model of the part
%NCY1a: Nominal cylinder of NM1
%NPL1c: Nominal plane of NM1
% Identification of the datum A
S1a = Partition(SM1,NM1,NCY1a);
CY1a = Cylinder();
D1aMIN = Dmatmin(S1a,CY1a);
CY1a = Association(CY1a,D1MIN> = 0,Dia(CY1a));
% Identification of the toleranced feature
S1c = Partition(SM1,NM1,NPL1c);
PL1c = Plane();
D1c = Dmax(S1c,PL1c);
A1 = Angle(Axis(CY1a),PL1c);
PL1c = Association(PL1c,A1 = pi/2,D1c);
% Evaluation of the perpendicularity deviation
DEV: = Eval(D1c);
RESULT: = Eval(DEV<=0.05/2);
```

Figure 3-11: Perpendicularity specification in GeoSpelling (Ballu *et al.* 2015)

Ricci *et al.* (2013a) developed the VerificationManager system that demonstrated an implementation of the developed categorical data model of compliance uncertainty and cost. The model was created using CT by Ricci *et al.* (2013b); it estimated the uncertainties and cost of a planned verification based on a flatness specification operator. Skin models defined in the ISO GPS series to represent the actual part boundaries that could result from the different machining processes were also investigated to assess their potential for tolerance analysis and simulation systems. Schleich *et al.* (2016); Schleicha *et al.* (2014); Anwer *et al.* (2014); Anwer *et al.* (2013) and Zhang *et al.* (2013) introduced the skin model shape concept as being a finite representation of the infinite skin models. These studies then explored the different approaches used for the generation of a digital representation of the skin model shapes with discrete geometry representations, such as point clouds and surface meshes. They expected that the skin model shapes could potentially support the assembly simulation with the consideration of the form deviation. Figure 3-12 shows the illustration of the skin model simulation for supporting tolerance analysis systems.

3.2. State-of-the-art in measurement process planning and system integration

Process planning is considered to be a bridge between design and other manufacturing activities; it converts design specifications into a sequence of required

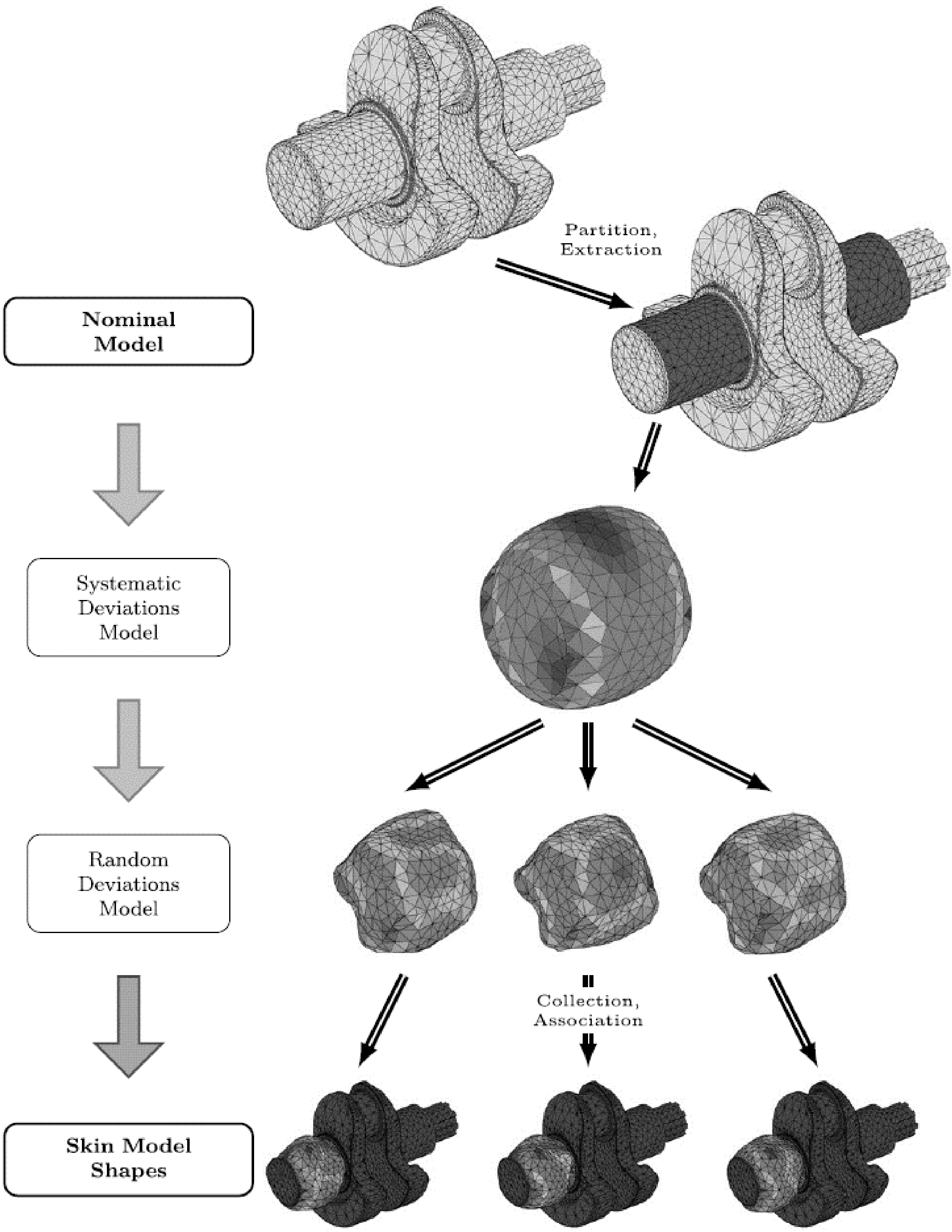


Figure 3-12: Skin model for tolerance analysis (Schleicha *et al.* 2014)

manufacturing actions. Xu (2009) mentioned the Society of Manufacturing Engineering (SME)'s definition for process planning as "the systematic determination of the methods by which a product is to be manufactured economically and competitively." Process planning includes the selection of the processes and technologies required for generating, assembling, or measurement a product given that it is a single part, configuration, or structure (Maropoulos 1995). Process plans can be divided into macro and micro planning modules. Macro planning includes the establishment of the best sequence of manufacturing, assembly or inspection. This sequence is related to the workpiece setups, feature interrelations and accessibility issues. Measurement macro plans aimed to minimise the overall part setups and sensor orientations needed to complete the measurement task when using a CMM, while depending on machining sequences when using on-machine inspection (OMI), (Zhao *et al.* 2009b). Micro-planning, on the other hand, involves decisions such as the generation of machining or measurement path and corresponding machine dependent code generation tasks. The determination of the measurement points' density and distribution is a unique measurement micro planning activity. The objective is to justify statistically a sufficient number of points and distribution to represent the entire surface population in a highly confident manner. Measurement plans can exist independently or as a part of the machining process plan. A measurement plan not only determines what, where, when and how the part characteristics are to be measured, but also how the measured data is to be evaluated.

Process plans can be classified based on their scope or the degree of automation (Elmaraghy 2007). From the automation perspective, process plans can be manual, computerised or automated. Manual planning lacks consistency, standardisation and optimality (Xu 2009). As a rule, computer-aided process planning (CAPP) is not necessarily automated, but automated process planning is, by nature, computerised (Elmaraghy 2007). The degree of automation can be classified as variant, semi-generative and generative. The variant approach is based on retrieval methods from existing databases, based on the design or manufacturing features similarities among parts (Elmaraghy *et al.* 2013). Retrieval method uses Group Technology (GT) and part family concepts. A master process plan is created for what is called a composite part, which includes all features that exist in a part family. New plans are created by identifying, retrieving and modifying the existing standards plans for similar parts. Semi-generative and generative process planning benefit from the retrieved master process plans to make some ''variant-specific'' changes. These changes are to make further decisions or to optimise some operations or parameters. Generative plans are achieved by using algorithmic procedures assisted by CAD models, databases, decision tables or trees, heuristics and knowledge rules (Elmaraghy *et al.* 2013).

Expert and Knowledge-based systems that use the domain experts' knowledge with tools such as geometric reasoning and artificial intelligence are generative approaches. In general, expert knowledge in manufacturing research is represented as a set of rules. The main elements of a knowledge-based system are knowledge modelling and representation, in addition to an effective inference mechanism. Chandrasegaran *et al.* (2013) reviewed different knowledge representation methods before focusing on the product design knowledge. On the other end of the scale, neural networks have been applied for the acquisition and for the update of expert knowledge. Genetic algorithms and fuzzy logic methods have been applied for different knowledge-based planning objectives (Maropoulos 1995). It should be noted that a complete generative process planning system has not been realised (Elmaraghy 2007). Measurement plan automation is still challenged by the lack of sufficient data that could be retrieved for its construction or the lack of defined practice standards. Measurement plans are based on the modular structure, in which some modules may be automated and the others not, but a fully automated measurement system is still a major research challenge.

Distributed, web-based or networked process planning approaches, as well as, reconfigurable process planning are new trends, which have evolved under the pressure of the decentralised manufacturing system and highly customised products. Agent-based CAPP is developed to meet the requirements of modern decentralised manufacturing facilities; collections of loosely connected process planning sub-systems, each with a limited function or scope, form a system of systems with an overall supervisory coordinating system. Reconfigurable process planning was first defined by Elmaraghy (2007) as being able to respond efficiently to both subtle and major changes in “evolving parts/products families” and reconfigurable manufacturing systems. It is considered as a soft enabler for changeability, in which plans are an act of insertion rather than an act of sequencing (Elmaraghy *et al.* 2013).

3.2.1. Measurement plans characteristics and system selection

As discussed in section 1.1, the consistency and the value of the gained measurement knowledge are heavily influenced by the measurement planning stage. Furthermore, measurement planning activity involves time-consuming and manual operations that cause serious bottlenecks in production lines (Lee and Park 2000), in addition to the resulting uncertainty of the overall measurement process. As a consequence, measurement planning should optimally be automated, integrated and efficient (Zhao *et al.* 2009b).

Automation is crucial as manual operation of measurement sensors depends on the intuition and feel of skilled workers. Operator-dependent measurement can take an extensive amount of time and often causes inconsistent results due to using trial and error based approaches. It is also necessary to avoid personal-dependant measurement decisions. Integration allows the seamless and timely exchange of data accurately for better manufacturing decisions and flexibility. Efficiency includes better measurement system and technology selection to accommodate the measurement task requirements, as well as, reducing the overall measurement cost and time.

Currently, measurement-planning methods are resource dependent, which means the measurement machine and technology should be determined as the first step. Measurement systems can be broadly classified as contact, non-contact and dual-principle systems (Mahmoud 2013). Contact measurement has the advantage of accuracy and traceability while non-contact measurement is competitive due to superior speed, flexibility and its non-destructive nature. It should be noted that the selection of measurement system determines the final achieved uncertainty and repeatability based on its capability specifications. Lin and Liu (1997) proposed a back propagation neural network example to establish a knowledge base system for choosing a CMM based on its measurement range and accuracy data. Son *et al.* (2003) also applied neural network techniques to perform measuring device selection based on the knowledge of the measuring parameters and measuring resources. In this work, 12 parameters are extracted from CAD system to understand the part under consideration and to assist the measuring device step. These parameters are described as extracted information in Figure 3-13. These parameters were extracted manually through applying geometric operations to the CAD data or by interactively defining it. In this work, the manual interaction was required during information extraction for completing data that did not exist in the CAD database. For example, Gaussian curvature or surface type can be obtained from CAD data while the standard deviation of normal and facet approximations was calculated from the geometric information. Figure 3-13 also illustrate some parameters that were used to represent measuring machines. In addition, Son *et al.* (2003) presented some visual illustration for measurement elements as shown in Figure 3-14.

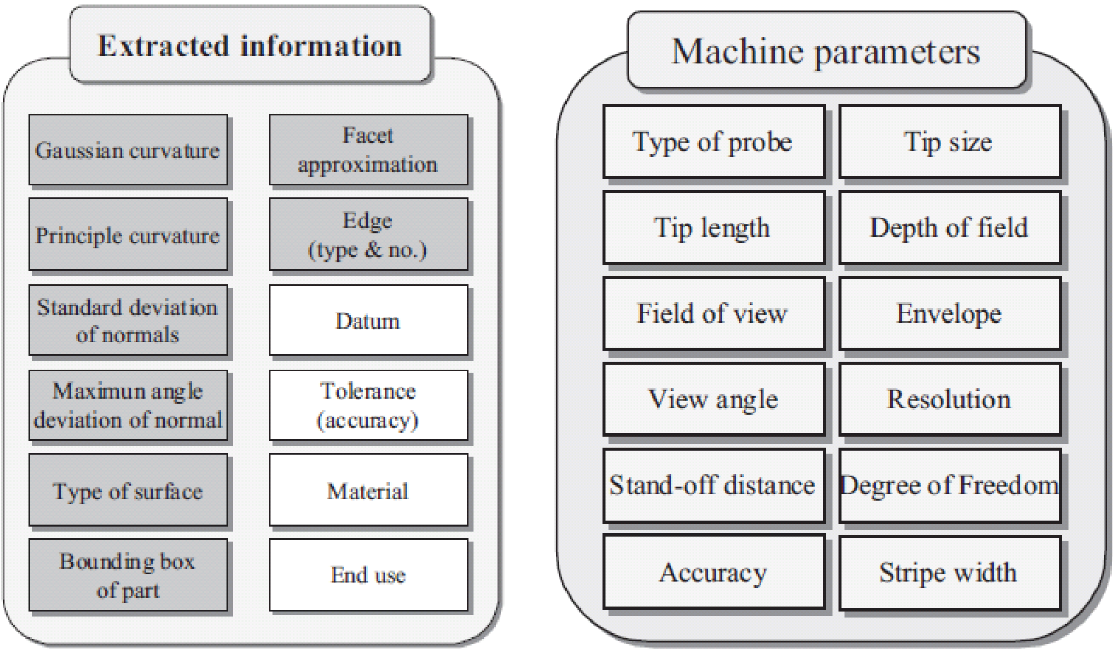


Figure 3-13: Machine parameters and selection criteria (Son *et al.* 2003)

Cai *et al.* (2010) performed a task measurability analysis based on a matrix mapping method. The aim was to match metrology instruments to specific measurement requirements. Figure 3-15 shows an example of this matrix mapping approach. The research used measurability characteristics (MCs) such as technology readiness level (TRL), physical capability, uncertainty capability and cost as matching parameters. Physical capability included measurement volume, material, stiffness and environmental conditions. Environmental factors were used to eliminate instruments whose operating limits fell outside the expected environment. The cost attributes included utilisation, deployment and operation costs. TRL reveals the maturity of measurement principles and systems that may affect the overall accuracy, stability and reliability.

Maropoulos *et al.* (2010) used database tables and data filtering methods to select suitable measurement system based on specific measurement application requirements. Simplified models for measurement uncertainty, time and cost were introduced. The environmental condition was represented by an acceptable fixed range while the portability was abstracted by required packaging volume and setup time. These studies ignored the need to check the possible physical access to the measurement instrument to the measurement area. In addition, the applied cost model neglected the effect of measurement uncertainty on part rejection rates and the accuracy requirements for other processes. By identifying the measurement equipment, other tasks are required for

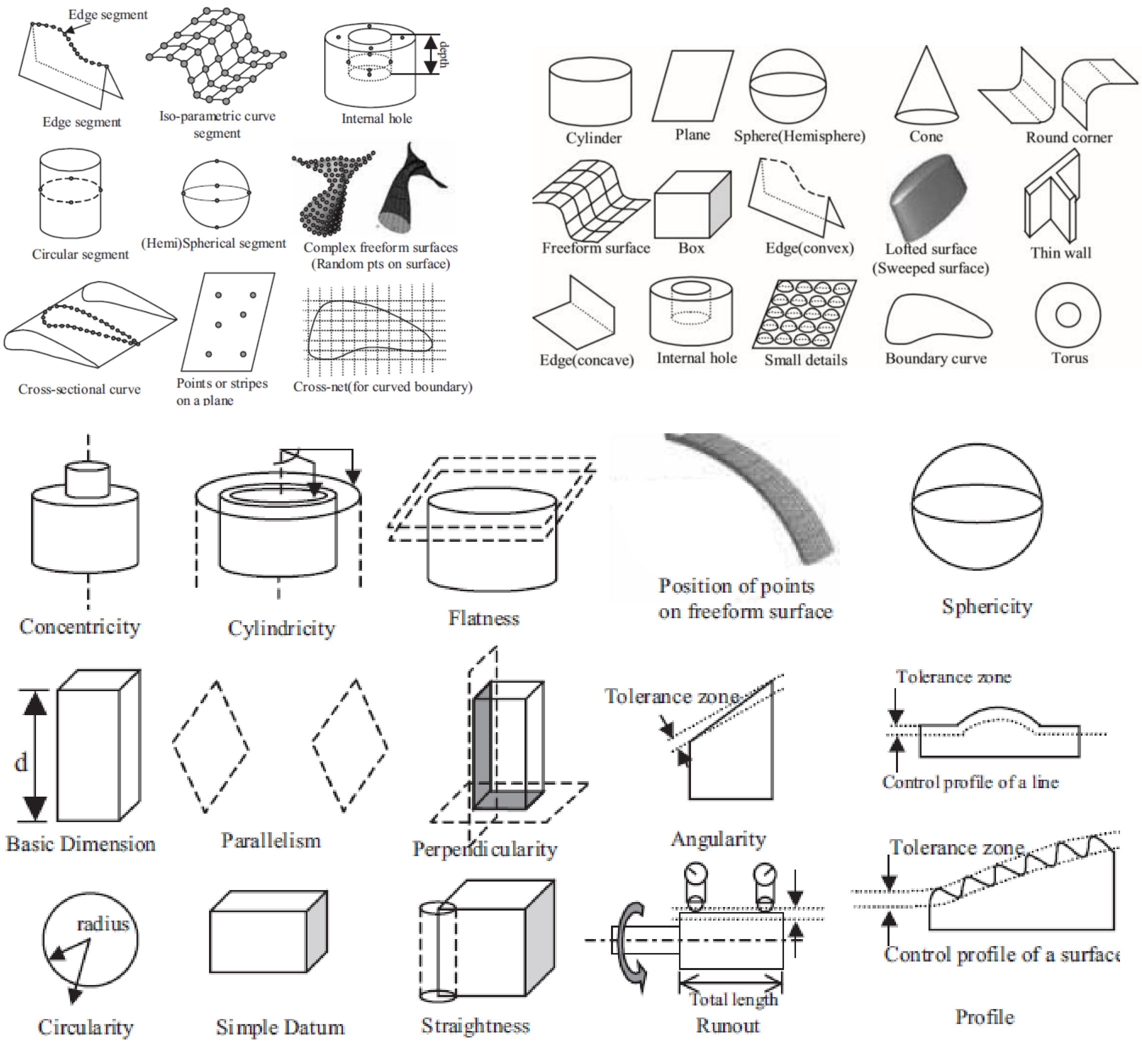


Figure 3-14: examples of measurement elements (Son *et al.* 2003)

completing the measurement plans; these will be discussed in more details in the following section.

3.2.2. Computer aided inspection planning

(i) Initial evolution period of coordinate metrology tools

Go and no-go hard gauges, pneumatic gauges, electronic gauges, dial indicators, callipers and micrometres are examples of the common tools applied for checking the dimensions or conformance of final products. By the introduction of coordinate metrology systems, manufacturing systems have benefited from its increased accuracy and flexibility levels, which are coupled with a reduction in the measurement time and cost (Hocken and Pereira 2012). The first versions of CMMs deployed hard contact probes that were controlled manually with some electronic coordinate readout devices.

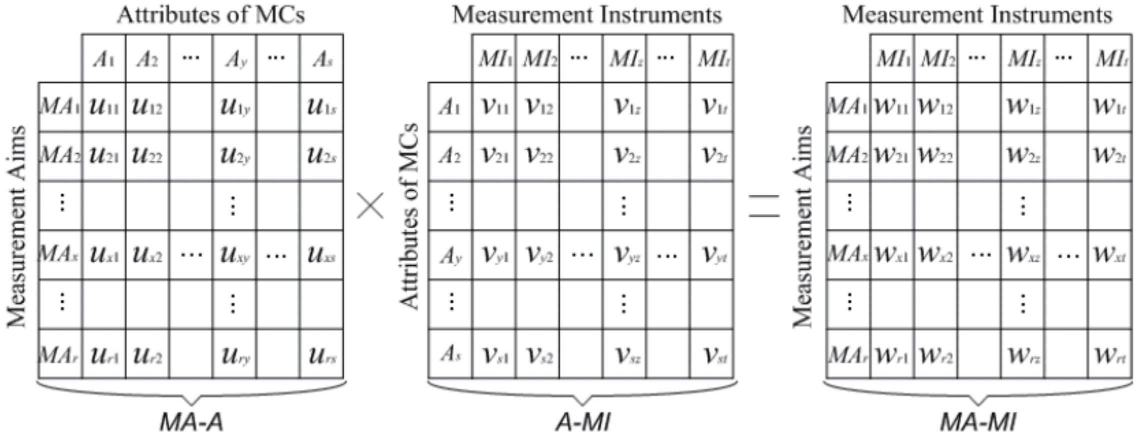


Figure 3-15: Matrix mapping for measurement system selection (Cai *et al.* 2010)

Computer technology has benefited CMMs' developments as CMM started to be controlled by computers. Automatic CMMs then were evolved and their software was full of different recording and analysis capabilities. Today CMMs are also equipped with a range of suitable sensors' technologies and accessories such as automatic probe changing and indexing devices.

The development in CMMs was accompanied by a continuous enhancement in software. Software capabilities that are continuously evolved include part programming, measurement data analysis, temperature compensation and geometric errors correction. Early studies aimed to increase CMM accuracy by providing software tools with error compensation mechanisms such as those presented by Hocken *et al.* (1977), Zhang *et al.* (1985) and Zhang *et al.* (1988). They introduced volumetric error maps and mathematical CMM models for error compensation. Early research also evaluated the newly evolved technology on different applications. Kawabe *et al.* (1980) tried to construct a surface geometric representation using uniformly sampled points to generate NC machining commands. Hermann (1985) also discussed the use of coordinate metrology and probing techniques as a tool for the characterisation of CNC machine tools.

At this early stage, concerns were focused on developing algorithms to guide the sensing process blindly or through the interface with CAD data. Jie chi *et al.* (1982) proposed a control algorithm to trace the unknown profiles automatically. The first record for CAD based planning or control was when Hopp and Hocken (1984) suggested a 7 level hierarchal control system for CMMs that started by manual information selection from a CAD database, which was later used for micro planning issues. Figure 3-16 shows the seven control levels and some of the required data for each level. In addition, this

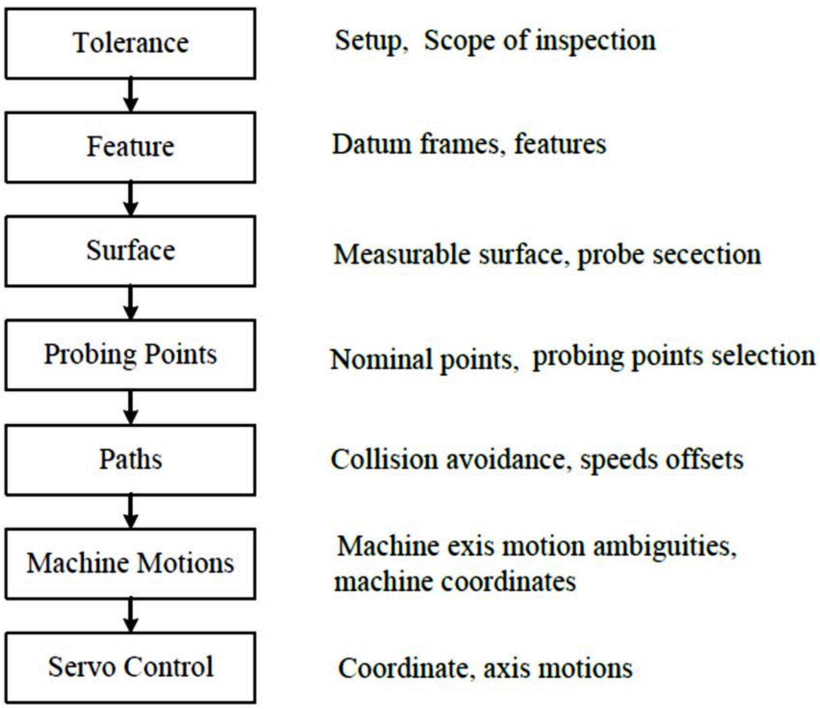


Figure 3-16: Inspection control hierarchy (Hopp and Hocken 1984)

work established a roadmap for the requirements of CAD-directed inspection systems. One outcome of this study the need for upgrading CAD databases for supplying necessary data for quality purposes. In addition, the requirement for knowledge-based rules for representing geometric reasoning and metrology principles was highlighted. Duffie *et al.* (1984) used CAD-based measured points to search for the closest CAD surface corresponding points through solving nonlinear equations using iterative minimisation methods such as the Newton-Raphson technique. Closest related points were used later for simple analysis task to evaluate the root mean square error of the overall measurement process.

The following period of this early coordinate metrology research could be divided into macro planning research and micro planning research. Both macro and micro measurement planning were investigated over a long period for CMMs and On-machine inspection (OMI). The developed contributions were focused on specific planning tasks or modules. Measurement modules can be broadly divided into measurement scope determination, sampling strategy, path planning and code programming (Zhao *et al.* 2009b).

(ii) Workpiece setups and accessibility analysis macro planning

As all inspection requirements are not commonly achievable in one part setup, the relationship between the measurement sensor and the part, as well as, the interrelations between the inspected features is a major research concern. Elmaraghy *et al.* (1987) proposed the first CAD-based knowledge-based macro inspection planning system for CMMs. Wireframe modelling, the PROLOG object oriented programming and syntactic pattern recognition methods were applied for reasoning and representing part prismatic features. Heuristic rules were used for the sequencing of the inspection tasks such as measure the datum features first and use same probe configuration first. This work considers the feature accessibility as a planning parameter, such that all features that are accessible from a defined probe configuration should be measured in sequence. Elmaraghy *et al.* (1987) also stressed the need for extending the design database to cope with measurement needs.

Spyridi and Requicha (1990) defined the local and global accessibility cones. The local accessibility cones are concerned with the features' surfaces, while the global accessibility cones are concerned with the entire workpiece surface. Khoshnevis and Yeh (1993) used techniques to slice 3D models into sections and studied accessibility using heuristics rules. Ray tracing was applied by Lim and Menq (1994), A. Limaiem and H. A. Elmaraghy (1997) and Limaiem and Elmaraghy (2000) to test the global accessibility cones for calculating the minimum number of probe orientations required to inspect the part. Yau and Menq (1995) computed accessibility for free-form surfaces. Ziemian and Medeiros (1997,1998) investigated accessibility to determine feasible sets of workpiece orientations on a CMM. Solid modelling operations were also applied to perform the accessibility analysis by Anis Limaiem and H. ElMaraghy (1997). A visibility map method was used by Kweon and Medeiros (1998) and Jackman and Park (1998) to represent the accessible directions from which measurements could be accomplished. Visibility maps were applied in different types of applications, but their underlying concept and theory were quite similar to the accessibility cones concept.

Spitz *et al.* (1999) used clipping operations to perform accessibility analysis using different probe configurations. Vafaeesefat and Elmaraghy (2000) determined the accessibility domain of a set of measurement points automatically and then grouped them into a set of heuristically created clusters. The system used an optical analogy method in which a hemisphere that contains the point normal vector represents the local accessibility cone of a point. Any accessibility obstacles were then projected on this hemisphere and then subtracted from it using clipping algorithms. The accessibility problem for rotational parts using a star probe was discussed by Rico *et al.* (2002). A methodology for consideration of probe length and volume to improve the probing accessibility results of CMMs was introduced by Wu *et al.* (2004). This method was based on projection techniques.

A heuristic algorithm to determine the inspection sequence was developed by Roy *et al.* (1994). The system directly interpreted the design data stored in the constructive solid geometry (CSG) model using a LISP program. Lee *et al.* (2004) developed a feature grouping and sequencing method for both machining and inspection activities. A series of heuristic rules and feature relationships were used for grouping and sequencing tasks. The nested relationship of the features was depicted in the precedence tree of the features, which graphically represented the geometrical parent and child relationship of the part features (sequence of machining). The system input was manually provided feature information with no interaction with CAD. The accessibility was simplified by considering the cutting tool approach direction to be perpendicular to the part face, and the inspection was performed with the same setup as machining. It was assumed that inspection planning is undertaken after machining process planning, which constrains the inspection sequences and setups for those decided for machining.

Hwang *et al.* (2004) used a heuristic method to obtain the minimal number of part setups and probe changes. The work applied a neural network approach to solve the inspection feature-sequencing problem. During sequencing, not only the travel distances between features were taken into considerations, but also, physical constraints and heuristic rules were included. Three rules were applied, they are: datum feature must be inspected consecutively at the very beginning of the sequence, the inspection features accessible in the same probe orientation must be arranged successively, and datum features must be arranged prior to the remaining features in the same probe orientations.

(iii) Sampling Strategy for extracting measurement data

Concerning the sampling strategy, Caskey *et al.* (1990), Weckenmann *et al.* (1995) and Weckenmann *et al.* (1998) discussed the effect of the sampling method on the accuracy of the final analysis results and the overall measurement uncertainty. Bichmann *et al.* (2004) emphasised that the consistency of CMM measurement results depends on measurement strategies, which are often defined differently from place to place and from user to user. The importance of finding standards for describing the measurement practice on a feature-based basis was then stressed. Weckenmann *et al.* (1995) clarified that sampling strategy is usually defined based on subjective criteria and experience, which may not be related to the functional requirements. In fact, the problem of sampling is to determine how many points are sufficient and how they will be distributed to represent the entire measured surface accurately. For freeform surface contact scanning, it is a matter of the number and distribution of the parametric scanning traces on the surface that the contact probe will move along in addition to a sampling rate based on time or distance (Rajamohan and Shunmugam 2013). Menq *et al.* (1992) proposed a Statistical method to determine the sample size based on the manufacturing accuracy and the tolerance specification.

The distribution of measurement points can be broadly divided into those applied for simple features and those applied to freeform surfaces. For simple geometries, the ISO14406 (ISO 2010b), specifies the possible extraction methods for different geometries. Other standards provide some recommend extraction methods, among those defined based on geometry for the measurement of a specific type of tolerance evaluation task (ISO 2011d, g, f, e). Figure 3-17 describes these standardised sampling strategies while Table 3-1 clarifies the valid sampling methods based on the given surface geometry type. Similarly, Figure 3-18 presents samples of advanced contact scanning strategies defined with the introduction of recent CMM probing heads such as REVO (Renishaw 2008). Uniform based, curvature based, mean curvature based, patch-size based and hybrid based methods are examples of freeform sampling strategies that give the number and distribution of lines to be scanned. Edgeworth and Wilhelm (1999) used an adaptive sampling method for cases with undetermined

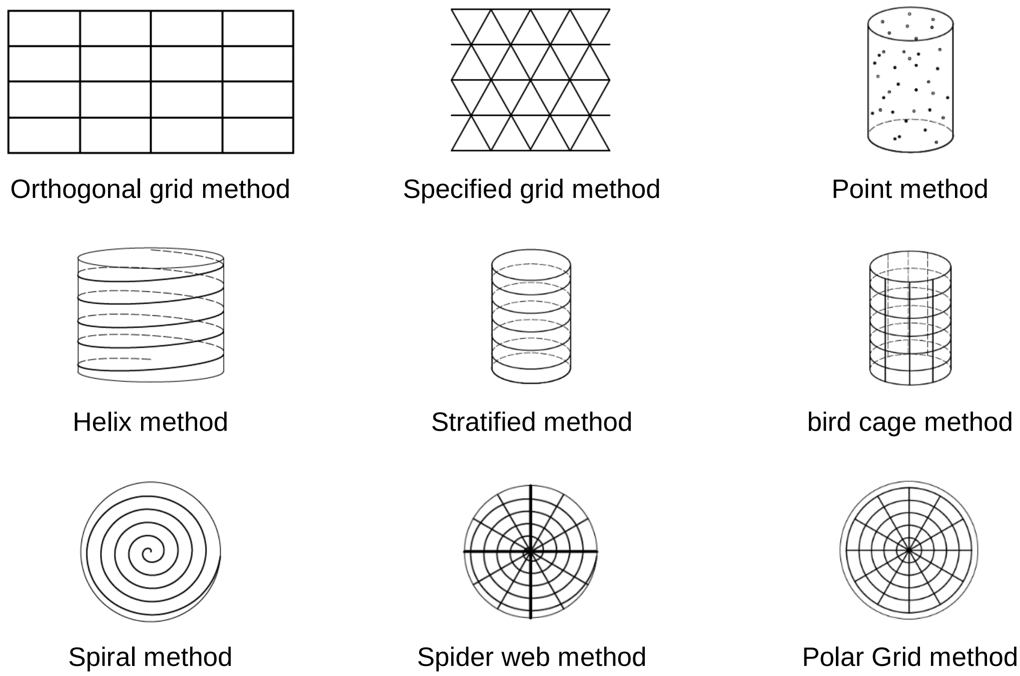


Figure 3-17: Sampling methods as defined in ISO14406 (ISO 2010b)

Table 3-1: valid sampling methods for different surface geometries (ISO 2010b)

Sampling strategy	Sphere	Plane	Cylinder	Surface of revolution	Prism	Helix tube	Complex
Orthogonal grid	X	X	X	X	X	X	X
Bird cage			X	X	X	X	
Polar grid		X					
Specified grid	X	X	X	X	X	X	X
Stratified	X	X	X	X	X	X	X
Helix	X		X	X	X	X	X
Spiral		X					
Spider web		X					
Points	X	X	X	X	X	X	X

sampling size. A literature of the sampling algorithms for freeform measurement can be found in (Rajamohan and Shunmugam 2013; Rajamohan *et al.* 2011; ElKott and Veldhuis 2005; Elkott *et al.* 2002; Elkott *et al.* 1999).

In the research performed by Cho and Seo (2002), an OMI strategy for sculptured surfaces was generated based on CAM data. Manufacturing errors were evaluated based on simulation methods and on comparisons with the original CAD model. Based on the simulated errors and the originally uniform-distributed points, two re-sampling methods were proposed. The first re-sampling was for the measurement performed after finishing operations by considering sensing that area with significantly predicted errors in simulation. The second re-sampling was for the measurement performed after roughing cycles by selecting the measuring points based on cutting tool path information to reduce inspection errors due to cusps.

(iv) Single sensor computer aided offline inspection-planning systems

Measurement planning research started by considering only the contact probing sensing technology, as the non-contact sensors were not mature enough during the early

Sweep scan Section scan Gasket scan

Figure 3-18: Contact-scanning strategies (Renishaw 2008) research period and required further development (Modjarrad 1989). Merat *et al.* (1991) developed a rule-based and feature-based measurement planning system. The inspection-code fragment (IFC) concept was introduced; it includes the instructions required to inspect individual features. By aggregating all these IFCs, the measurement plan can be constructed. Yau and Menq (1992) and Chia Hsiang Menq *et al.* (1992) developed knowledge-based intelligent planning system that used interactive user access (IUA) to generate the inspection attributes. A decision-making component together with, inspection knowledge and artificial intelligence technologies were utilised automatically to generate inspection points, probing vectors, probing sequence and inspection path for each inspected feature. Medland *et al.* (1993) integrated the design data with the probing strategy for CMM measurement. This work was a part of the 'IPSCIS' research project at Brunel University. This project aimed to reduce the CMM non-productive programming time. Geometry data from a feature-based STEP file was extracted manually; the tolerances were then added manually to the selected features. Probing geometry, approach vectors, probe data, probe configurations and probing path was then generated by the system.

An offline micro measurement planning system, limited to positional tolerances of a single shallow cylindrical hole, was developed by Kim and Chang (1996). Offline measurement planning is to plan the inspection based on the CAD data and without operating a CMM. This system consisted of three modules as illustrated in Figure 3-19; they are data input module, the measurement planning module and the statistical analysis module. The tolerances data, the features and the used probe were manually selected. The sufficient number of measuring points that allow the measurement result to be with a predefined confidence level was calculated based on a proposed statistical method. Kim and Chang (1996) argued that measurement plans should be based on tolerance information and not on features, as interrelations between different features are as much important as intrinsic parameters of each feature.

Hermann (1997) developed a feature-based off-line programming system for CMMs. The user can interact with a CAD interface to select the surfaces to be inspected. The user then manually adds tolerance data as additional information. The proposed plan was continued through the user-based selection of the measuring machine, probing system and the workpiece setup. The sampling strategy was elected with an expert rule-based routine from available feature-based strategies, which could be overridden later by the user. Finally, a local measurement path is constructed using a heuristic approach.

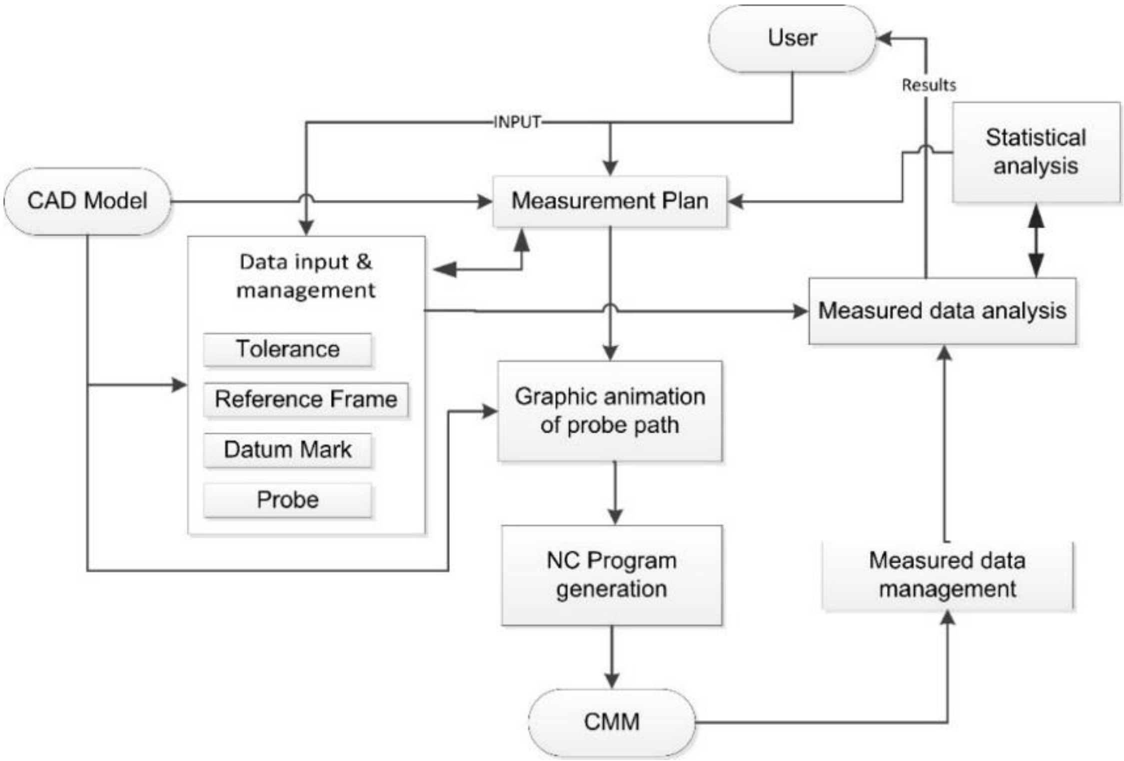


Figure 3-19: Offline system for inspection automation (Kim and Chang 1996)

The system used ACIS as the geometric modelling engine and ProKappa as a shell for the decision-making process.

A feature-based offline inspection planning system for CMMs was developed by Zhang *et al.* (2000). This system consisted of five modules. These modules are tolerance feature analysis, accessibility analysis, clustering analysis, path generation, and inspection process simulation and are illustrated in Figure 3-20. The first module was used to input tolerance data and its relations to features. The accessibility analysis for a feature was calculated using a Gauss map and the clustering using weighting factors. A knowledge-based clustering algorithm was used to group inspection features into clusters to reduce the measurement time. Finally, the path generation module determined the number, distribution and sequence of the sampling points. The measurement point density was between 5 and 15 based on feature type and standard specifications. A simulation could follow to check the probe path and any probable

Figure 3-20: Five modules in offline measurement planning (Zhang *et al.* 2000)

collisions. The number of sampling points was limited to 6 or 12 based on the tolerance type. Zhang *et al.* (2000) concluded the inability of CAD systems to store tolerance information and hence used what Zhang *et al.* (2000) called as frame based data structure to relate inspected features to tolerance data.

Sathi and Rao (2009) proposed a system to generate automatic inspection plans for a CMM based on a CAD model. Three modules were used; they are geometric information manipulation, automatic setup planning and probe path generation. They deducted that decisions related to CMM measurement planning are operator dependent. This work proposed integration with the CAD system through STEP file edition 2, which includes tolerance information, defined within the STEP framework. It should be noted that the author stated that the information in the STEP file was not available in the desired format required by the inspection application, and thus validation and synthesis steps were necessary. The accessibility directions were based on the selected probe type. The probe selection is made through an algorithm that traverses a probe library to get probes suitable for accessible directions of a specific feature. Thirty-two uniformly distributed points were selected for inspecting the features based on their industrial experiences.

Later, Cho *et al.* (2004) developed a new local inspection planning strategy, by decomposing each manufacturing prismatic feature into its constituent geometric elements. For each geometrical element, the suitable number of measuring points, the measuring points locations, and the optimum probing paths to minimise measuring errors and time were calculated. The fuzzy set theory, the Hammersley's algorithm and the travelling salesman problem (TSP) method were applied. A collision-checking algorithm was proposed based on the Z-map concept and was validated by simulation. The same work of the global and local inspection planning system was repeated for CMM measurement by Cho *et al.* (2005).

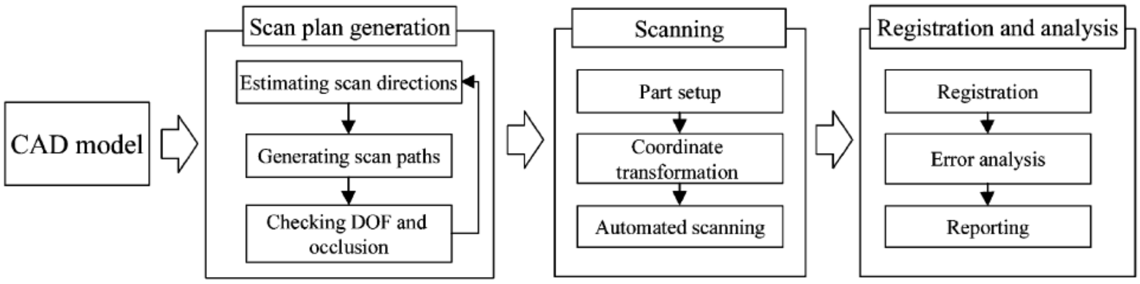
Although the capabilities and requirements of noncontact laser triangulation sensors for dimensional inspection was evaluated by Goh *et al.* (1986), noncontact methods only reached the level of maturity required for applied in practical measurement applications by the late 1990s. The application of non-contact sensors increased due to the need for reverse engineering and the need to measure complex surfaces in different applications. Griffa (2008) discussed the main differences between the traditional CMM measurement process and how its working framework could be changed if noncontact methods are used with it. Lee and Park (2000) developed a three-module laser-scanning based measurement plan for 3-axis CMMs. The system started by calculating the accessible direction for measurement points created along iso-parametric surface curves. These accessible directions are then clustered based on a heuristic approach to determine the scanning directions. Accessibility analysis considered the constraints embedded due to the scanning sensor, such as its viewing angle, depth of view and laser strip length. In a later stage, the number of scans and the scanning path were evaluated. For the registration of multiple scanned data from multiple orientations, a rotary table was used. Geometric operations are done by using CATGEO library routines provided by the CATIA. This study did not take into account the optical characteristics and roughness of the inspected surface as well as ambient illumination.

Son *et al.* (2002) proposed an automated laser scanning measurement plan for complex surfaces. Hardware for correctly positioning and orienting the workpiece with respect to the scanner was used, which also assisted in the automatic registration of post-measurement operations. Scanning parameters were considered during the planning phase and were compared to the distances between measurement points for the determination of the critical points. The considered scanning parameters are such those considered by Lee and Park (2000) but in addition occlusion issue was considered. The scanned directions were decided based on differences in point normal information; this information was compared with the angle of view of the laser sensor. Finally, the system generated the number of required scans and the scan path needed to fulfil required inspection task. Figure 3-21 illustrates the different steps within the proposed laser scanning planning system.

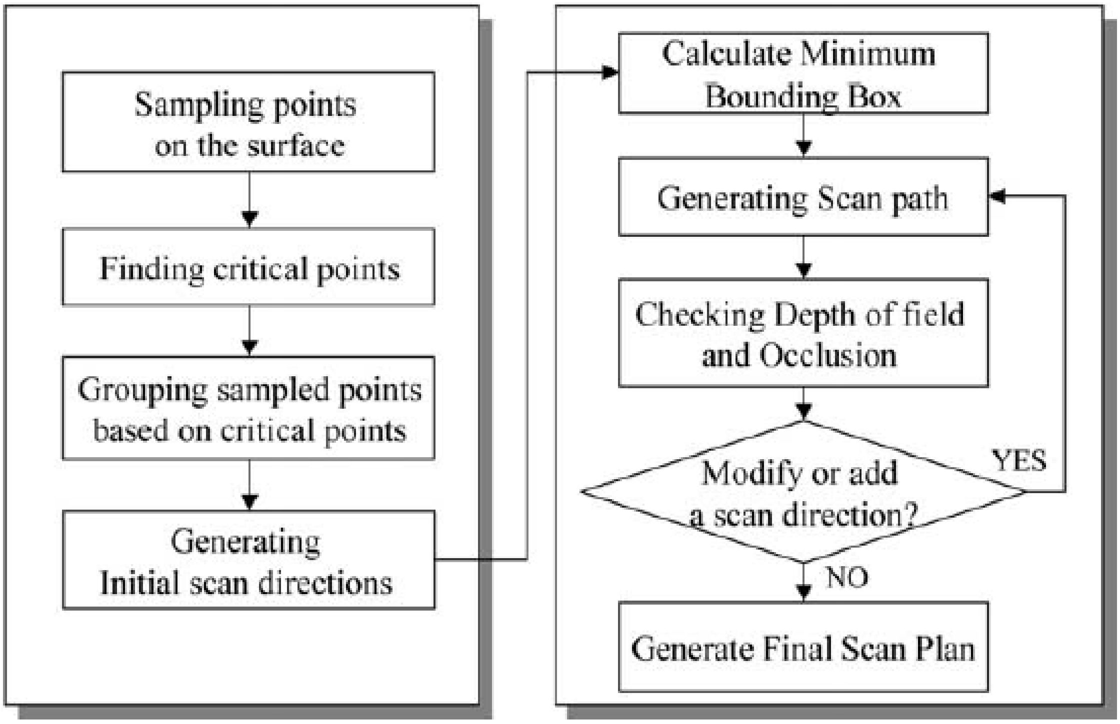
Elmaraghy and Yang (2003) presented an offline laser scanning system. The planning system was developed using ACIS geometric kernel and C++ software. The visibility problem was analysed using view angle, the field of view and depth of view limitations of the laser sensor. Large concave features that violate depth of view limitations were suggested for inspection using probing methods. A clustering algorithm based on the view angle and depth of view was used to obtain optimal scanner placement and scanning path. Simulation methods were used to validate the planned path in an offline manner. Figure 3-22 illustrate the main system modules.

(v) Multisensory computer aided offline measurement planning

There is no single method today that satisfies all the measurement tasks' environments and requirements (Beraldin 2004), in addition to being fully automated. Multi-sensor systems and data fusion techniques are therefore of importance. Multisensor systems can be used cooperatively or complementary to reach full coverage



(a)



(b)

Figure 3-21: Freeform inspection execution (a) and planning (b) steps using laser scanning (Son *et al.* 2002)

or to increase overall measurement accuracy or speed. One sensor is used for capturing global part information while the other was applied for additional precise measurements using the gathered global information. Multisensory inspection uses laser triangulation scanning sensors, video cameras and conscopic holography methods in conjunction with contact probing. Multisensory measurement has been investigated from the data fusion point of view. Weckenmann *et al.* (2009) reviewed the data fusion in multisensory for inspection systems.

The first theoretical consideration for a planning system for multisensor measurements was discussed by Bichmann *et al.* (2004) when two research projects

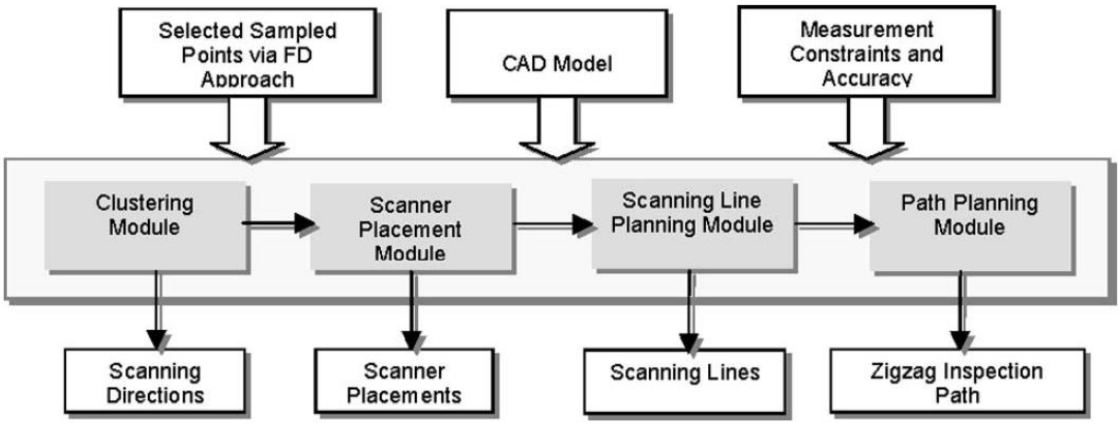


Figure 3-22: Laser scanning planning structure (Elmaraghy and Yang 2003)

investigated the integration of optical metrology into the present quality and machine tools systems. The first project was to integrate a conosopic sensor into a CMM and the other project was to integrate a laser scanning triangulation sensor into an automated repair cell based on laser welding and 5 axis CNC milling machines. During the first project introduction, the extraction of the inspection feature was planned to be done through the link between STEP geometry-based data and the Q-DAS for tolerances information. During the second project illustration, the sensitivity of the optical sensor to the machining environment was raised as an issue to be investigated, and some heuristic knowledge-based strategy was set for both laser scanning and probing measurement.

Haibin Zhao *et al.* (2006) proposed an inspection plan for CMM based on the analyses of neutral interchange files such as STEP and QDAS. Based on the extracted data from the analysis step, a sequence of inspection planning tasks was generated. These tasks included point placement, probe orientation-based accessibility evaluation and the free collision path planning. Finally, a DMIS program for CMM was generated. The point placement was designed based on hybrid uniform and curvature-based distributions. The author alleged that the developed system integrated non-contact measurement devices, conoscopic holography and camera sensors, with traditional contact probing method for the measurement of a complex surface. The work proposes an expert knowledge-based database to support the automatic selection of the suitable measurement technique based on the measurement task, but there was not enough description on how this was done.

By combining both the knowledge-based systems and the optimisation methods, Mohib *et al.* (2009) proposed a practical hybrid sensor inspection planning system. The system automated the optimal sensor-task assignment using a proposed inspection-specific features taxonomy. The sequencing of the hybrid inspection tasks was developed by using a modified TSP, in which a sub-tour elimination constraint was formulated. The research involved a touch probe and a laser scanner Metris LC50, mounted on a gantry-type CMM. A water pump housing case of an automotive engine study was used to apply the proposed system. The general algebraic modelling system (GAMS) and CPLEX optimisation solver were used to implement the modified TSP. Table 3-2 show the result of the output of the proposed system.

Later, Haibin Zhao *et al.* (2012) investigated a hybrid inspection system based on contact probing and laser scanning as well. Figure 3-23 show the proposed system framework. Inspection features are identified and constructed based on CAD models. A knowledge-based sensor selection approach was applied for each inspection feature. Two inspection-planning modules were designed for each sensor type. Contacting inspection planning consisted of sampling and path planning. The Hammersley algorithm and uniform sampling methods were applied; the final sampling strategy was checked through uncertainty simulation techniques. The laser scanning plan, on the other hand, consisted of view angle calculation, scanner elevation determination and scan path generation modules.

(vi) Samples of commercial software CMM applications

The author has reviewed the specifications of different commercial measurement software and this section describes two selected measurement planning applications that are currently used in the market. These two applications were selected by the author to presents the current capabilities of measurement applications for both CMM and on-machine measurement. The author concluded that commercial measurement planning

Table 3-2: Optimal inspection operations' order results developed (Mohib *et. al.* 2009)

	Feature Name	Recommended Probe		Part Orientation	Probe Orientation		Starting Point		
Op	i	Sensor	j_i	P_{ij}	A_{ij}	B_{ij}	x	y	z
5	Datum C: Reversed conic hole	Laser	1	1	0	0	40	−75	5
3	Datum B: Bottom cylinder	Laser	1	1	45	45s	50	−25	60
14	Slide wall	Laser	1	2	45	45s	70	60	0
12	Slide	Laser	1	2	45	45s	−20	70	0
11	Innlet/outlet	Laser	1	2	45	90s	−40	100	0
9	Rotor cone	Laser	1	2	0	90s	75	20	20
16	Prismatic hole	Laser	1	2	0	0	−10	10	0
8	Clearance holes	Laser	1	2	0	0	−10	110	0
1	Datum A: Gasket surface	Laser	1	2	0	0	−50	100	0
2	Datum A: Gasket surface	Touch	2	2	0	0	−50	100	0
13	Slide	Touch	2	2	0	0	−20	70	0
7	Tapped holes	Touch	2	2	0	0	7	25	0
10	Cylindrical step	Touch	2	2	0	0	50	−20	30
15	Slide wall	Touch	2	2	0	0	70	60	0
4	Datum B: Bottom cylinder	Touch	2	1	0	0	50	−25	60
6	Datum C: Reversed conic hole	Touch	2	1	0	0	40	−75	5

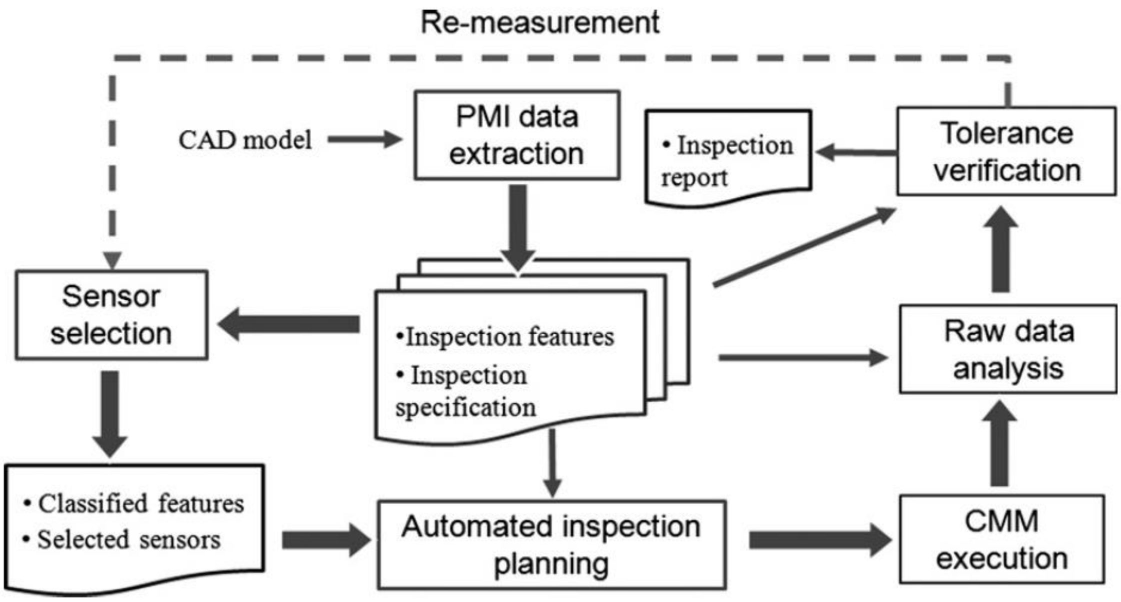


Figure 3-23: Inspection process framework (Haibin Zhao *et al.* 2012)

systems are not mature enough for developing automated measurement plans based on integrated interfaces with CAD or CAM platforms. Recently many updates of the standardised information and knowledge could help in bridging this gap, even the purpose of the standards development was concerned with CAD-CAD data exchange for visualisation issues.

With regard to the recent software announcements, Hexagon Metrology (2014) described PCDMIS-Planner as a tool for translating ordinary GD&Ts to a set of programming lines for CMM. This software depends on user tolerance selections using CAD interfaces and converts these manual selections to feature and tolerance definition lines in a DMIS program. This information is insufficient to build up a complete measurement plan or program that means further user interactions and decisions are still needed. Examples for these are to define evaluation parameters, evaluation rules, feature sampling strategy, filters and procedures to be applied. As an example for OMI, Productivity+, produced by Renishaw (2013), can be considered as a user interface for supporting manual selections among different options rather than an inspection planning program. One mentioned software from CMM market and the other for OMI, both still require manual intervention either to define the inspection scope or to complete the measurement plan by the micro or analysis data.

3.2.3. Measurement integration and interoperability

As part of the manufacturing systems, the measurement should be automated and integrated to capitalise the benefits of modern, flexible measurement resources and to cope with the increased demands for customised products. Recently, standard and academic communities raised awareness of the importance of the measurement processes' interoperable integration, as its economic potential in manufacturing has started to be understood and quantified (Savio *et al.* 2014; Savio 2012). By the development of STEP standards, many researchers studied the ability to integrate the measurement process or the measurement process data with the overall manufacturing systems.

Kramer *et al.* (2001) discussed the integration problems between manufacturing components and the lack of open interfaces between different systems modules that challenges the interoperability. Kramer et al. (2001) deducted that open formats are of less importance unless they are standardised. In their research on assessing the feature-based technology for planning machining and OMI, Kramer *et al.* (2001) proposed a feature-based control system (FBICS) hierarchical architecture, as shown in Figure 3-24. The proposed control system was implemented at NIST. The system consists of a cell, workstation and task controllers where each controller contains two-stage planning modules. Communication interfaces among modules are APIs, messages or file interfaces. The system used STEP AP224 as the standard description of the machining features. The process plan was represented by A language for process specification (ALPS) at the cell and workstations module, while by RS274 and DMIS at the task module.

Concerning inspection in FBICS, two inspection tasks were defined for the workstation planar. The two inspection tasks are to measure a feature based on its removed volume index or to measure a surface; only the first were implemented after resolving the necessary decomposition of the manufacturing feature into multiple DMIS features. Difficulties regarding the user-dependent nature of the measurement process were identified and discussed. During the system implementation, these difficulties were treated through a user-defined preferences file including qualitative indicators about sampling density such as low, medium and high. It was not clear how the DMIS format was adopted for the OMI, but standard languages' interpreters were used to post-process input and output data for both planning and execution phases. Through post-processing, measurement results were fed back to the planning stage; this capability was discussed in the context of adaptive planning. Furthermore, the problematic decision about how many features should be machined before measuring some specific features has not been taken into consideration during the implementation. Liu *et al.* (2014) alleged

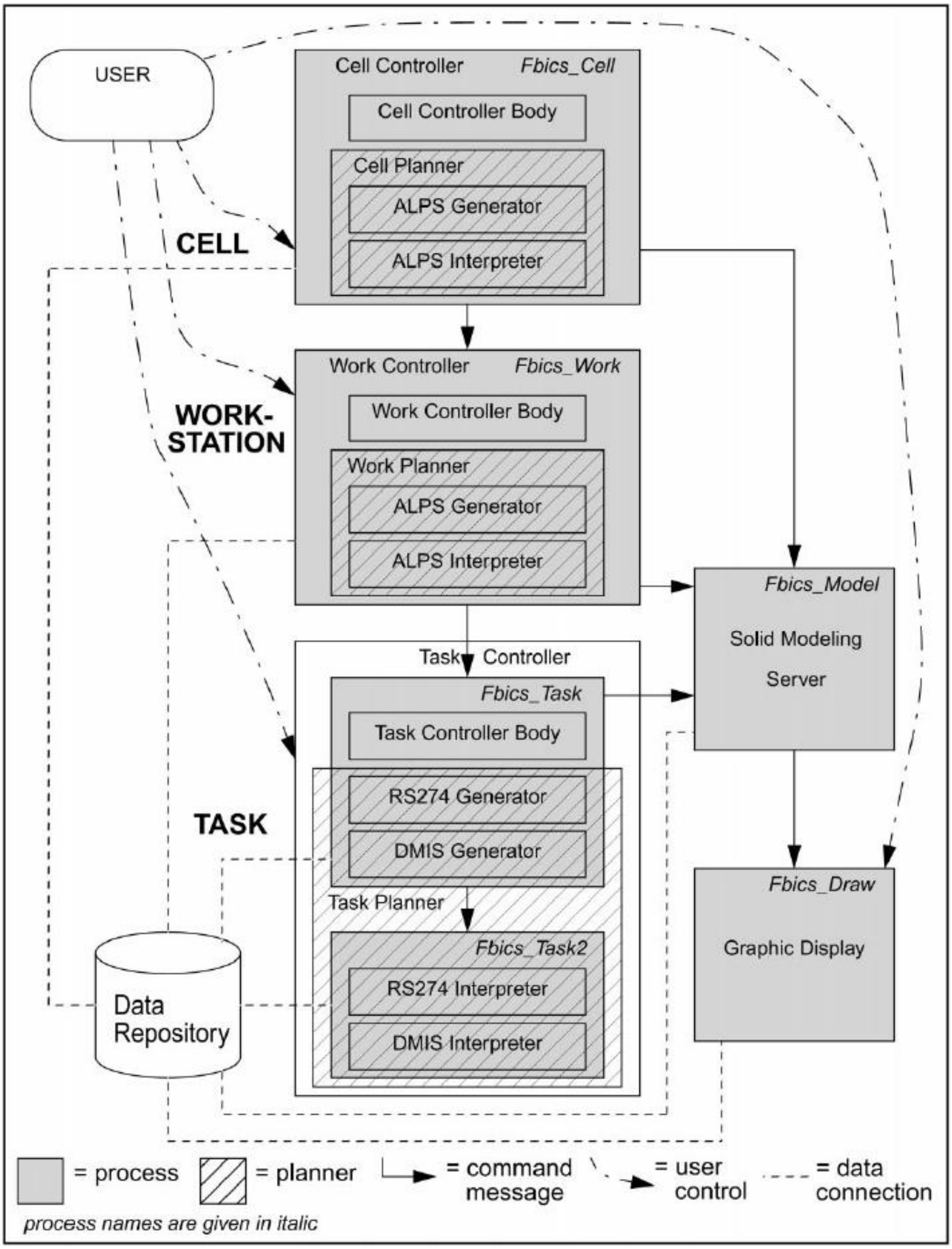


Figure 3-24: FBICS control system architecture (Kramer *et al.* 2001)

a solution for this problem through triggering the OMI by the monitoring sensors, in an integrated real manufacturing process monitoring and inspection system.

Under the objective of integrating the measurement system within the manufacturing system, a measurement system analysis was necessary to enhance and support the understanding of the measurement system. Within this scope, Lin and Chow (2001) used the IDEF0 and EXPRESS to perform system analyses and to construct the related data model of CMM measurement system. The EXPRESS data model was divided into three simple modules; namely, a part, a resource and an input data module.

By the same system analysis methodology, IDEF0, Barreiro *et al.* (2003b) investigated the functional requirement of CMM inspection system. EXPRESS and EXPRESS-G languages were used to represent the related data structures. Information requirements were divided into 13 groups according to their functionality. Figure 3-25 shows these 13 information groups as being identified by the system functional analysis through IDEF0 diagram. The information groups were grouped later in two main models: the product model and the process model. The completely developed model is made up of 240 entities, a full description of all entities was presented in Barreiro(2001), cited by Barreiro *et al.* (2003b), p.798. Figure 3-26 and Figure 3-27 show the data model for representing the inspection element and inspection plan respectively. This data model element is highly related to this thesis as one contribution of this work is how these data models for that element is more developed to cope with modern advances.

Later, Barreiro *et al.* (2003a) presented functional, reference and interpreted information models based on the STEP standard methodology. Inspection Framework

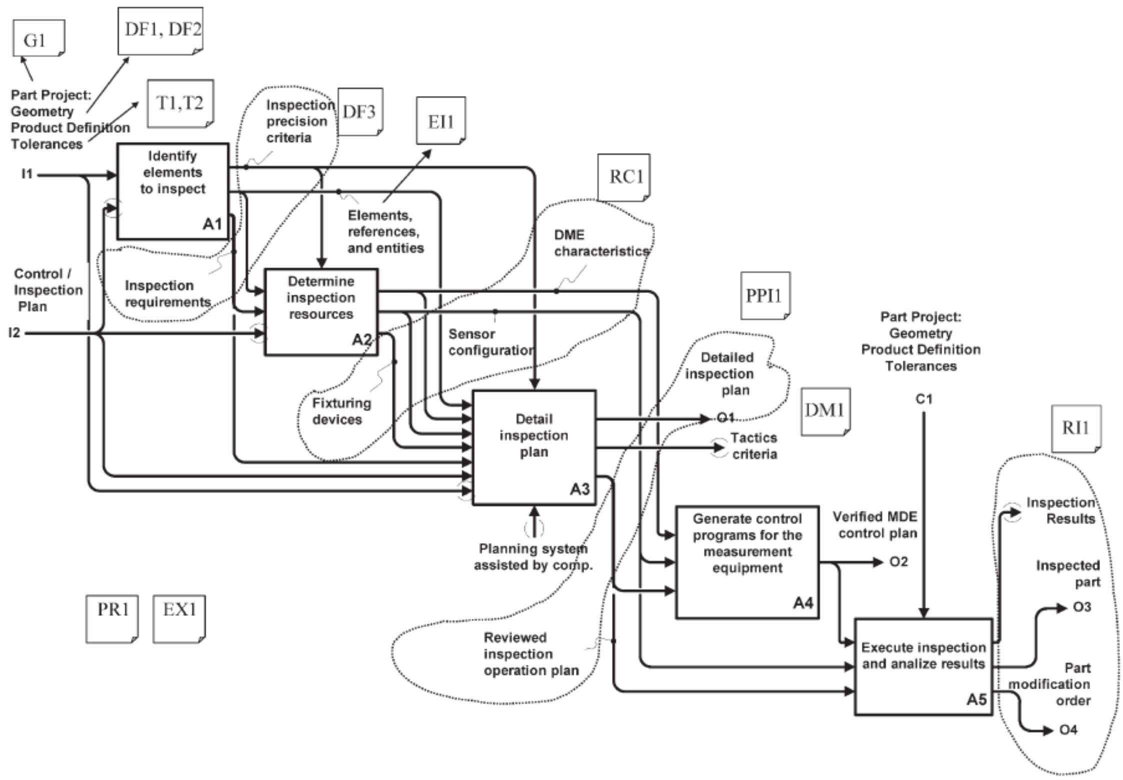


Figure 3-25: Measurement information groups (Barreiro *et al.* 2003b)

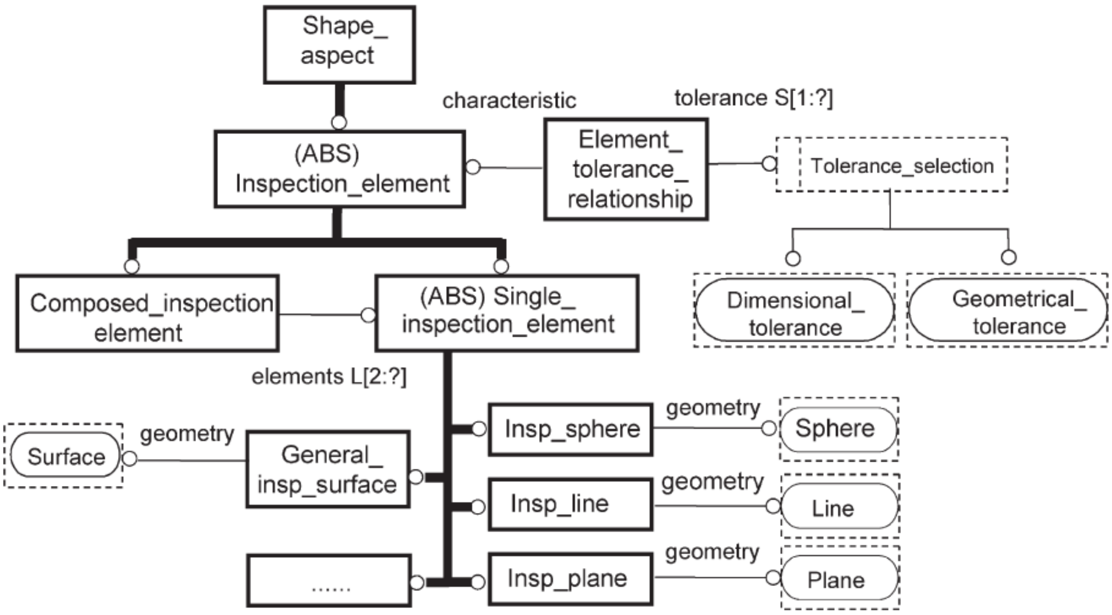


Figure 3-26: Inspection element data representation (Barreiro *et al.* 2003b)

for Concurrent Information Access (IFCIA), shown in Figure 3-28, has been developed to verify that the data structures can satisfy the information requirements associated with the inspection process. The IFCIA architecture is composed of a product modelling

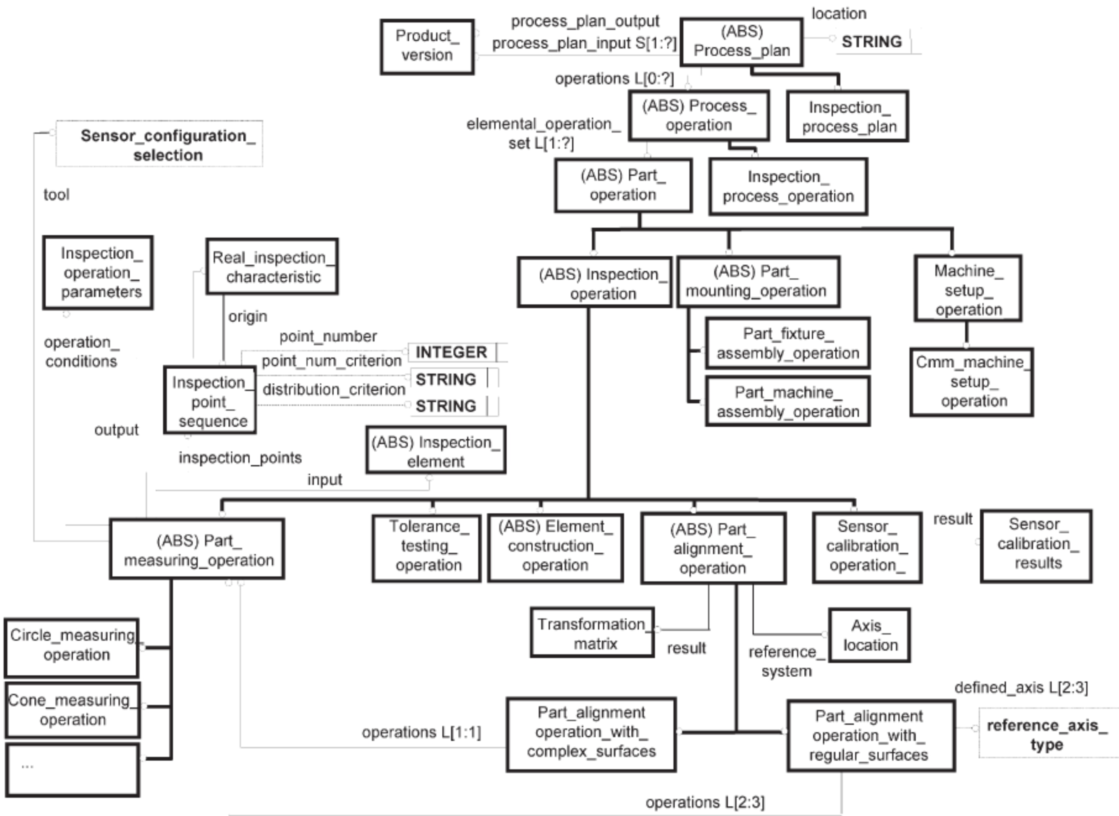


Figure 3-27:Inspection plan data representation (Barreiro *et al.* 2003b)

system, an object-oriented central database and a DEA CMM. CATIA has been used as a modelling system. The framework analysis included only prismatic and revolved features. For integrating measurement with CAD stage, CATIA API specific functions were deployed.

In the demonstration of the IFCIA framework, Barreiro *et al.* (2005) highlighted that the connection between the central database and the CMM is one of the main difficulties when integrating the inspection process with the rest of the activities in the cycle. Mapping tables were proposed as a solution in both directions, but Barreiro *et al.* (2005) reported that this violated the targeted integration objectives. A set of subroutines has been developed to extract the information related to the part program from the central database such as the probes approach/retract sequences, the sensor used and the operation parameters. A feedback of the inspection results was done, through mapping-tables, towards the product modeller to close the cycle completely.

Ali *et al.* (2005) and Ali (2005) developed an STEP-NC compliant inspection framework with the objective to construct a universal representation of the measurement process of prismatic parts. The idea behind this research was to study the ability of

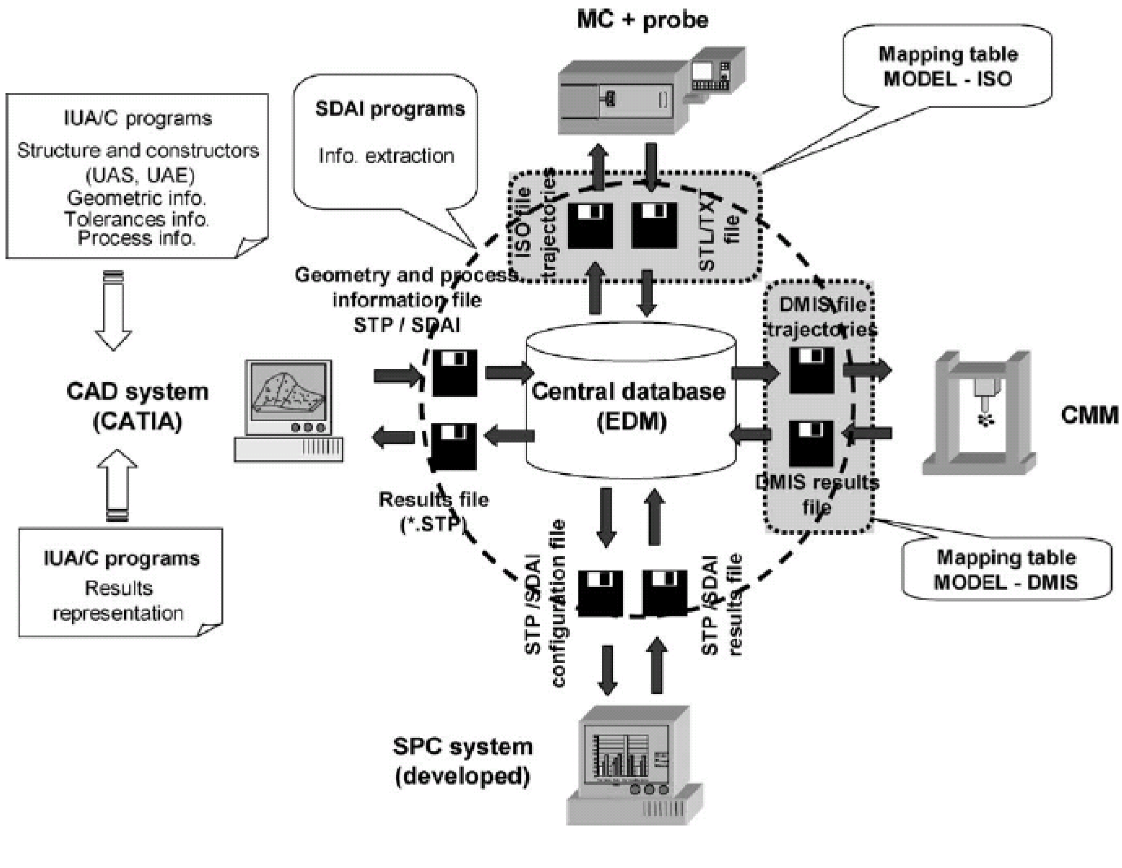


Figure 3-28: Extended inspection framework communications (Barreiro *et al.* 2005).

ISO14649 part 16 to be this universal framework for measurement data. The developed system input was a STEP AP224 file containing the manufacturing features while the GD&Ts were represented through DMIS and ISO14649 part 16 formats. This research output was an STEP-based file including only the probing data as an inspection workingstep; also, the measurement results have been recorded. Figure 3-29 shows a comparison between the traditional approach and the proposed one by Ali (2005). In fact, this study shared some aims with this work; however, to make the STEP-based measurement data universal, an extended method is suggested to overcome part 16 limitations; the full description of the significant limitations of ISO 14649 part 16 is given in subsection 4.1.7. The proposed modification is achieved by designing the data model from a scratch system analysis to show the data that is resource-independent, and based on the STEP methodology instead of limited STEP-NC for OMI. In addition, the author believes that measurement process definition is not limited to the extraction information but rather the analysis information that will process the extracted measurement data.

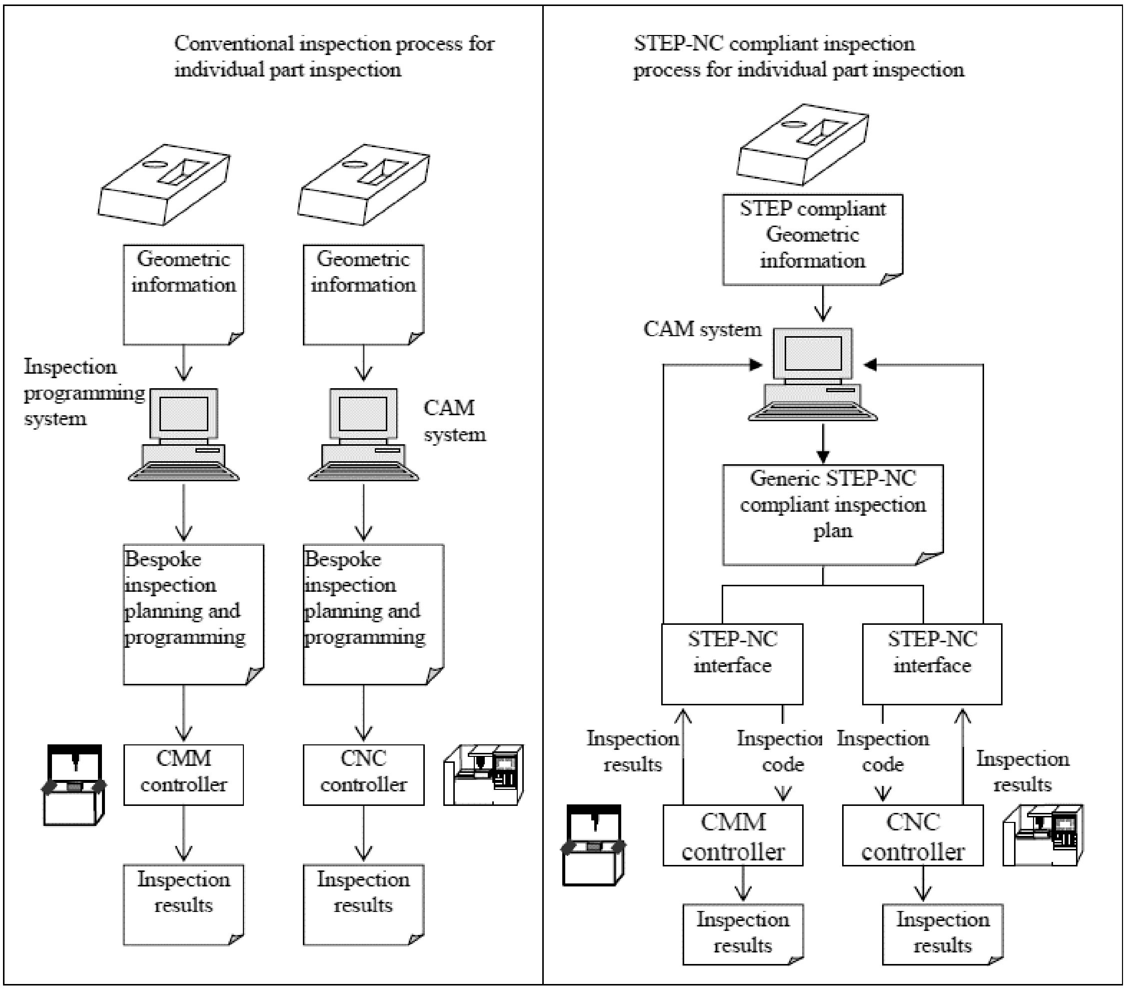


Figure 3-29: Traditional and STEP-NC measurement approaches (Ali 2005)

To achieve a closed STEP-NC-based process chain, Brecher *et al.* (2006) proposed integrate measuring technology into the STEP-NC framework to enable the feedback of the inspection results to the planning stage. Brecher *et al.* (2006) discussed the STEP, STEP-NC and the measurement standards, before discussing the benefits of feeding back the OMI results. A prototype scenario for the closed-loop process chain was illustrated. The scenario included generation and execution of an STEP-NC program and feedback of measured results to the CAM system. The functionality of the developed prototype was previously demonstrated by WZL at Aachen University, the scenario structure and the implementation framework could be illustrated by referring to Figure 3-30.

Zhao *et al.* (2008) built an STEP-NC data model for a closed loop manufacturing (CLM) system. The idea behind the work is to integrate OMI results with machining information. Design data were represented as a STEP AP203 file; features conforming to STEP AP224 were then constructed. The STEP-NC compliant CAPP system finally generates an STEP-NC file including information for both machining and inspection processes which is then sent for the CNC for the execution process. New entities were defined to store probing data and inspection results. The inspection results were used for modifying the STEP AP238 file for the machining the next parts. A case study,

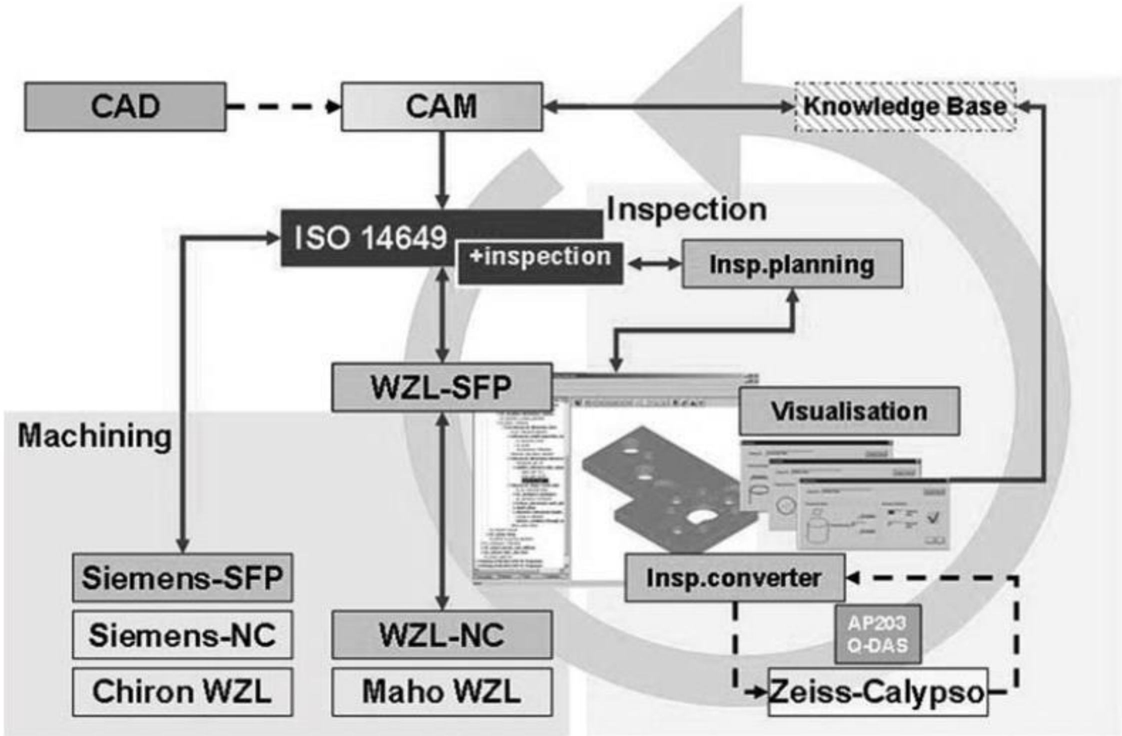


Figure 3-30: STEP-NC based inspection system implementation (Brecher *et al.* 2006)

containing prismatic features and based on the example in ISO 14649-11, was included to demonstrate the implementation. Zhao and Xu (2010) improved the model toward a consolidated model for an integrated process planning for both machining and inspection based on STEP standard to enable measurement feedback and automatic insertion of the OMI working steps within machining operations. Figure 3-31 shows an EXPRESS-G diagram of the defined inspection data while Figure 3-32 shows the consolidated machining and inspection planning framework. A software prototype, STEP-INSPEC, was developed to test the proposed data model capabilities.

Zhao *et al.* (2011b) discussed the challenges of the metrology system interoperability in its four main activities thoroughly. A proposed STEP data model was then discussed, to provide a standard to support automatic measurement plan generation for in-process on-machine measurement. Zhao *et al.* (2011b) supported the view that for ensuring the interoperability of the measurement plans, it should be device-independent; resource-independence is what this dissertation investigates.

By the introduction of the QIF standard, recent research started to investigate its ability toward ensuring the interoperability of the measurement system data. The QIF framework will be discussed thoroughly in section 4.4. Yaoyao Zhao *et al.* (2012) discussed QIF as being planned as individual application area standards supported by

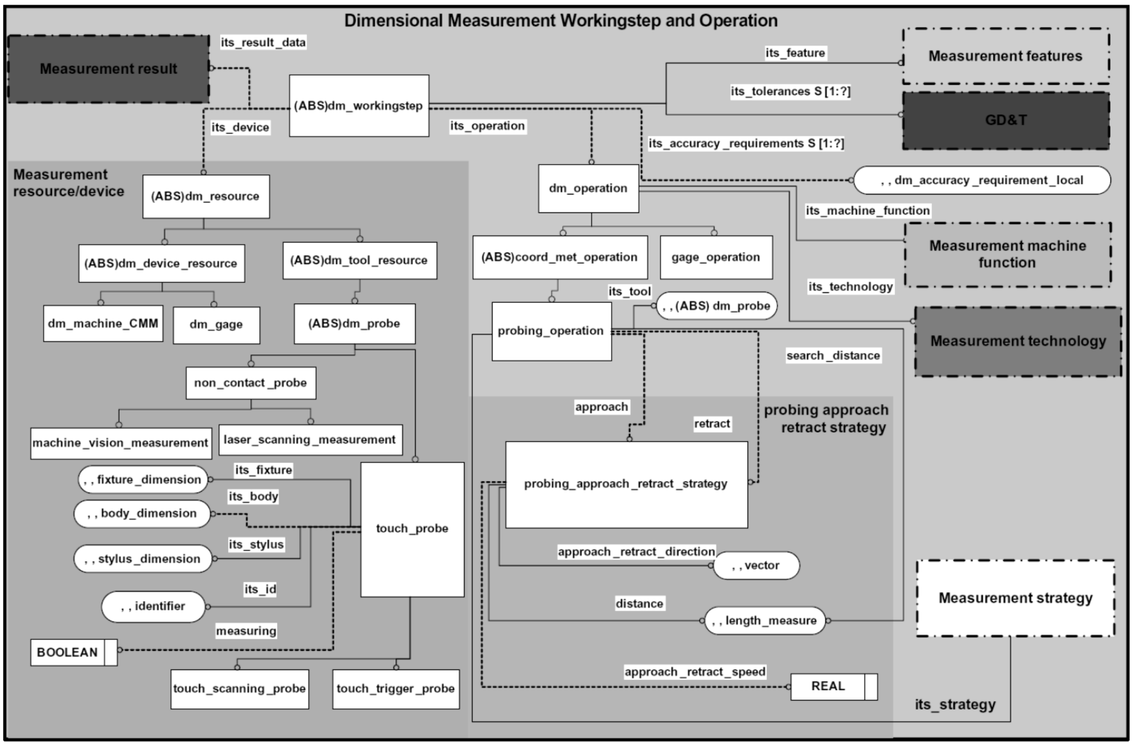


Figure 3-31: Inspection data model (Zhao and Xu 2010)

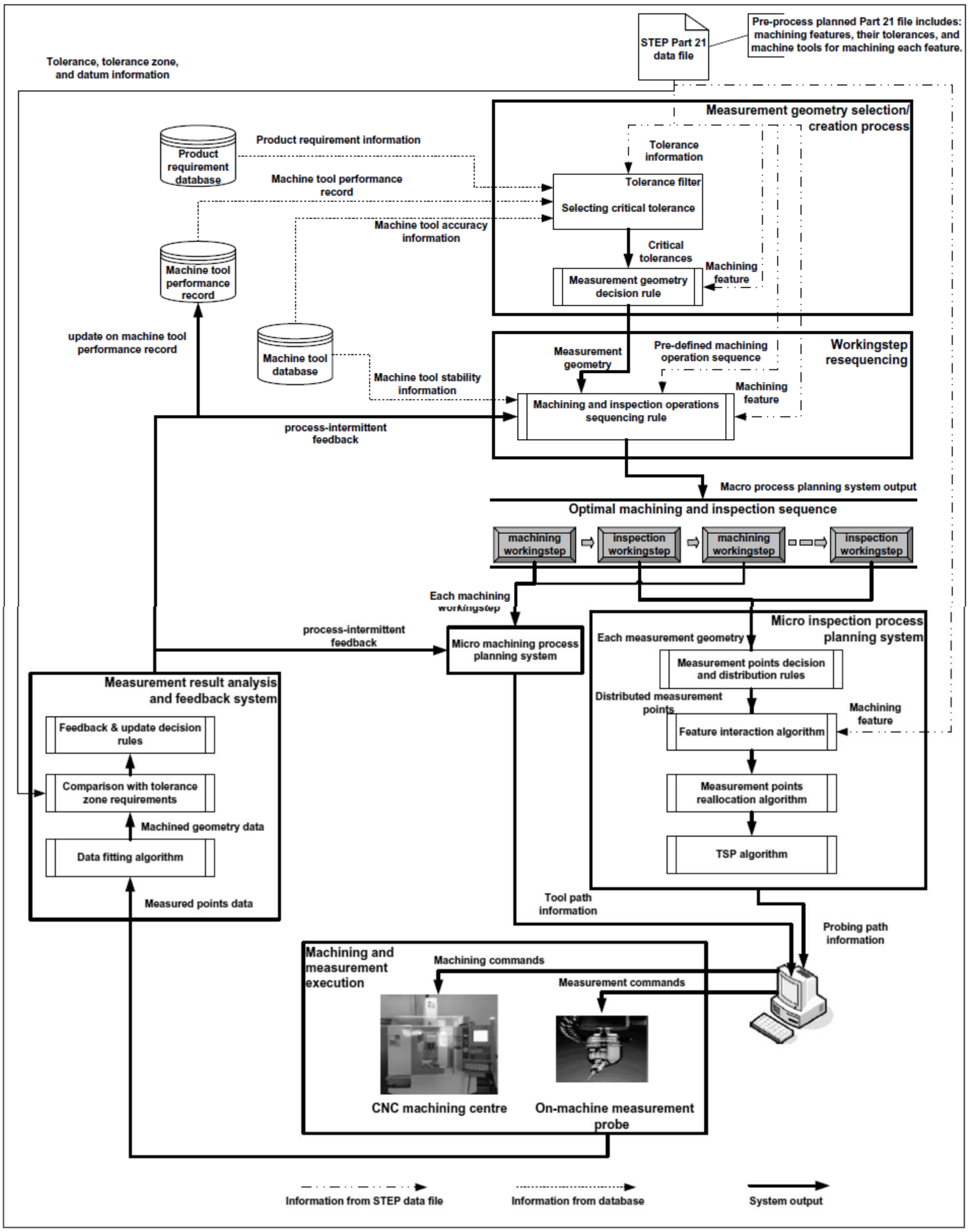


Figure 3-32: Integrated process planning system (Zhao and Xu 2010)

common data types and generic structures to promote reuse and inheritance throughout the QIF modules. Feature definitions include 28 feature and almost all of these features are equivalent to those defined DMIS 5.2. Michaloski *et al.* (2013) presented a pilot implementation of QMResults module, in the first QIF version, to produce a Web-enabled, real-time communication of quality results. MTConnect technology was used to communicate quality data using XML. The implementation was done using the NIST shop floor machine tool with measurement capabilities.

3.3. Recap and critique of academic measurement research

Section 3.1 portrayed the efforts done to provide a complete 3D representation of the design product embodiment by the PMI data to achieve the full applicability of solid models in digital manufacturing. The objective was to obtain an authoritative 3D model used as the main and sole source of information within PLM to reduce or eliminate manual interventions during downstream applications (Fischer *et al.* 2015). The author agrees with Anwer *et al*. (2014) and Hatman *et al.* (2012) in that currently the supply chain still relies on 2D design drawings despite being in digital manufacturing era; this nature of the supply chain is inefficient as it increase the required time, efforts and costs.

A number of researchers (Haibin Zhao *et al.* 2006; Barreiro *et al.* 2003b; Imkamp 2005) have attempted to address this problem through investigating linking tolerances data with data provided by open standards exported from CAD stations via CAD's internal API functions or through linking STEP data with Q-DAS data. Later, researchers evaluated the initial tolerances representation within STEP framework (Sathi and Rao 2009), where a tolerance validation and synthesis steps were necessary as the tolerance information was not represented in a suitable format for the direct use by inspection applications.

Later, the concept of MBD has begun to be conceptualised to make the product lifecycle more model-centric (Fischer *et al.* 2015). The author supports the opinin of Quintana *et al.* (2010) in that more efficient measurement processes are achievable by adopting MBD formats in industry. A computer readable tolerance information became necessary and gained the interest of many researchers. However, these GD&T representations was designed to fulfil the tolerance analysis needs (Shen *et al.*2008); rather than measurement applications requirements (Ziaoping Zhao *et al. 2006; Lemu 2014)*.

The author recognised that recently the ISO standard organisation has carried the burden of improving PMI representation to complete the MBD to improve open standardised formats. The state of the art developments toward representing PMI data within open standardised data models will be presented thoroughly in subsection 4.1.5 and this work is based on these latest developments while considering the data input to the developed REIMS prototype implementation system as shown in Figure 7-1.

Section 3.1.2 addressed the challenges related to the deviation of the applied coordinate metrology methods from the standard definitions of design specifications. This deviation has been recognised as a source of variability in the measurement process that affects the final results' uncertainty (Ballu *et al.* 2015). The author is of the same opinion of Vemulapalli *et al.* (2013) in that uncertainties in measurement results are not only due to hardware inaccuracies but also due to the applied software uncertainty and the improper selection of analysis algorithm during the planning phase. This latter source of variability is addressed by this research through the introduction of the REIMS framework that provides a mean to represent measurement analysis operation. This also emphasises the need for standardised good measurement practice guides and for the requirements for testing the conformance of the applied measurement software (Mani *et al.* 2011*;* Vemulapalli *et al.* 2013*)*.

Ballu and Mathieu (1996), Dantan *et al.* (2008) and Ballu *et al.* (2015) have introduced the GeoSpelling philosophy to provide elaborate tools for the designer to specify more accurate and measurement oriented part characteristics. The GeoSpelling language is proposed for the ISO standards community and this resulted in the introduction of ISO GPS standard framework presented in section 4.2. The ISO GPS is considered the theoretical basis of this work as it is the only standard considers the specification and measurement in relation to each other.

The ISO GPS framework also provides elaborate tools for reducing ambiguity and misinterpretation of design specifications (Lu *et al.* 2008). The introduced GeoSpelling concepts were used to support the design process by guiding the designer through the knowledge required for correctly specifying a part model to accommodate various functional requirements (Ballu *et al.* 2015; Xu *et al.* 2011; Lu *et al.* 2010; Qi *et al.* 2010; Lu *et al.* 2006; Wang *et al.*2006). In this context, the author supports the Ballu *et al.* (2015)'s view in that GeoSpelling should not only used for expressing design specifications but also should be applied for simulating measurement, assembly or manufacturing. This work adds the possibility to benefit from GeoSpelling and ISO GPS principles to enable data exchange and integration of measurement process definitions.

In sections 3.2.1 and 3.2.2, the author recognised that the measurement planning is a complicated stage because it includes various modules and decisions; they are time-consuming and cause bottlenecks in production lines (Lee and Park 2000). These modules are: the selection of measurement system, the analysis of accessibility and part setups, the sequencing of measuring actions, the decision on sampling strategy and the planning of the measurement path. These activities have been divided in the literature into macro and micro planning categories. The author, through the literature survey, has gathered the key characteristics of an optimal measurement plan as summarised in Table 3-3.

As discussed in subsection 3.2.2, a number of researchers have studied measurement plans independently or dependently on the machining process plans as for CMMs and on-machine measurements. The author noted that the knowledge used during measurement planning varied between different researchers as no standardised or documented verification knowledge is available. Moreover, measurement planning systems were strongly linked to specific measurement equipment (Zhao *et al.* 2011b). The author supports Zhao *et al.* (2011b)'s argument that the measurement process definition should be device-independent to ensure its interoperability.

The resource-independence philosophy introduced in REIMS framework means that measurement process definition should be formulated regardless of the used measurement equipment; however, this does not mean that the measurement process definition should not take into consideration the applied sensors' technology used during the data extraction phase of the measurement process. This resource independence but technology specific strategy is similar to the strategy followed during the introduction of the STEP-NC (ISO 2003) standard (Vichare *et al.* 2009; Nassehi 2007).

Table 3-3: Characteristics of optimal computer aided inspection plans

Characteristics	Description
Task Specific	Feature-based inspection plans
Interoperable	No conversion or data translation is required
Standardised	Follows standards, best practice guides and rules
Compatible	Measurement strategies are not defined differently from place to place or from user to user depending on inspector's intuitiveness
Complete	Include resource uncertainty and traceability information, applicable for all feature types and does not need any manual decisions
Generic	Inspection plans that contain information models for both contact and non-contact measurement resources to inspect both prismatic and complex freeform geometries
Flexible	Adaptable and responsive to dynamically changeable parts and part families' characteristics

In section 3.2.3, the modelling and integration of measurement process with machining phase were considered. It has been realised that interoperable integration of measurement process has a potential economic benefits (Savio *et al.* 2014; Savio *et al.* 2012). The feature various dimensionality in machining and measurement was identified as a problem that needs further steps during measurement integration (Kramer *et al.* 2001). Kramer *et al.* (2001) also clarified the user-dependence problem included during the definition of a measurement plan. Measurement system analysis was mandatory for understanding the data requirements necessary for modelling the measurement process (Lin and Chow 2001; Barreiro *et al.* 2003a; Barreiro *et al.* 2003b). The author views the REIMS framework as an extensive elaboration of the simple models defined by Barreiro *et al.* (2003b) for defining both products and processes rather than resources. It was highlighted that the absence of STEP-based measurement equipment hinders the full integration of the measurement process (Barreiro *et al.* 2005; Brecher *et al.* 2006); the author agrees with this argument and hence the REIMS framework is designed in a STEP-based manner.

Many efforts have been reported to integrated measurement through STEP framework (Ali *et al.* 2005; Brecher *et al.* 2006; Zhao *et al.* 2008; Zhao *et al.* 2010). The author recognised that these researches focused on modelling measurement probing tools, probing points and the feedback of the measurement resulting data to achieve closed loop manufacturing concept. The author concluded that the literature thus neglected the decisions related to other measurement technologies and data analysis required for evaluating extracted data during the definition of the measurement process. Hence, this work through the REIMS framework is required to extend the specification of measurement plans to include these previously neglected aspects. Finally, the author believes that a measurement process data model should be design in a holistic manner to accommodate different measurement requirements such as conformance checking, process control or even reverse engineering requirements.

To summarise, measurement research can be broadly classified into the following directions:

1. Assisting computer aided measurement-planning applications through the enhancement of measurement planning algorithms.
2. Improving and testing of deployed analysis routines within measurement software to ensure that final analysed results conform to GD&T standard definitions.

3. Formulating a standard format for representing measurement data for integrating measurement results with manufacturing data or statistical analysis applications based on STEP standardised frameworks.

In addition, the researchers have attempted to address challenges including:

1. **The ambiguity of design specifications** their **misinterpretation** due to the lack of proper representation of GD&Ts within the standardised neutral CAD formats for measurement applications.
2. **Lack of measurement-planning automation** due to the involvement of **operator-dependent decisions** due to the lack of standardised good practice guides for measurement processes.
3. The **absence of a general-purpose measurement process model** that satisfies different measurement purposes and can exchange all the necessary data for defining a measurement process seamlessly **without sacrificing design and manufacturing contexts**.
4. **Lack of measurement planning interoperability** as it is resource dependent due to the implicit link between measurement planning and programming tasks. Pre-selection of the measurement execution equipment becomes a constraint on the measurement plans that hinders its interoperability between different execution systems.
5. **Neglecting the planning decisions necessary for processing the extracted data** toward the final evaluation tasks during the definition of the measurement processes. Considering such neglected data contributes to lowering the overall variability of measurement results as it reduces the number of human-based decisions taken during the measurement phase.

4. State-of-the-art in the standardisation of measurement process data-exchange

This chapter focuses on recent developments in the standardisation process related to the work scope defined in section 2.4. Section 4.1 presents the STEP standards series as a widely accepted standard for digitally representing and exchanging data related to both products, assemblies and processes throughout the product lifecycle. The STEP architecture and standard development history will be briefly described and the methods used for modelling and implementation within STEP will be explored. These methods are adopted in this research to design and implement the STEP-based data model of measurement information. The concepts and definitions introduced in the next generation ISO GPS are presented in 4.2 to form the theoretical foundation of this work. Section 4.3 provides an overview of the DMIS standard, as the commonly applied programming format for CMMs. As being a programming format for measurement process, DMIS provides a framework that defines general measurement process requirements, actions and steps necessary to perform a defined measurement task. Finally, in section 4.4, the recently published QIF standard for measurement data will be explored as it is considered as the only standard that shares some objectives of this work.

4.1. The STEP framework of standards

STEP is a collection of ISO standards known as ISO 10303. STEP is a standard that is designed to allow product data exchange and sharing across the product lifecycle (Kramer and Xu 2009; Newman *et al.* 2008; Feeney 2002; Mason 2002). The STEP main objective is to represent unambiguously product information in a common computer interpretable format that enables its exchange independently from any particular computerised application as reported in ISO 10303-1 (ISO 1994a). Product data is information that can completely specify or identify product such as material, shape, GD&Ts and features. Product data also includes data required for managing, documenting, archiving and securing data that specifies product data. Figure 4-1 presents some examples of product data within the STEP scope that can be identified from a part drawing.

STEP was developed as a result of the increased need for standardised digital communication means that support global manufacturing. It is an interoperability enabler that ensures seamless and bidirectional communications among various manufacturing

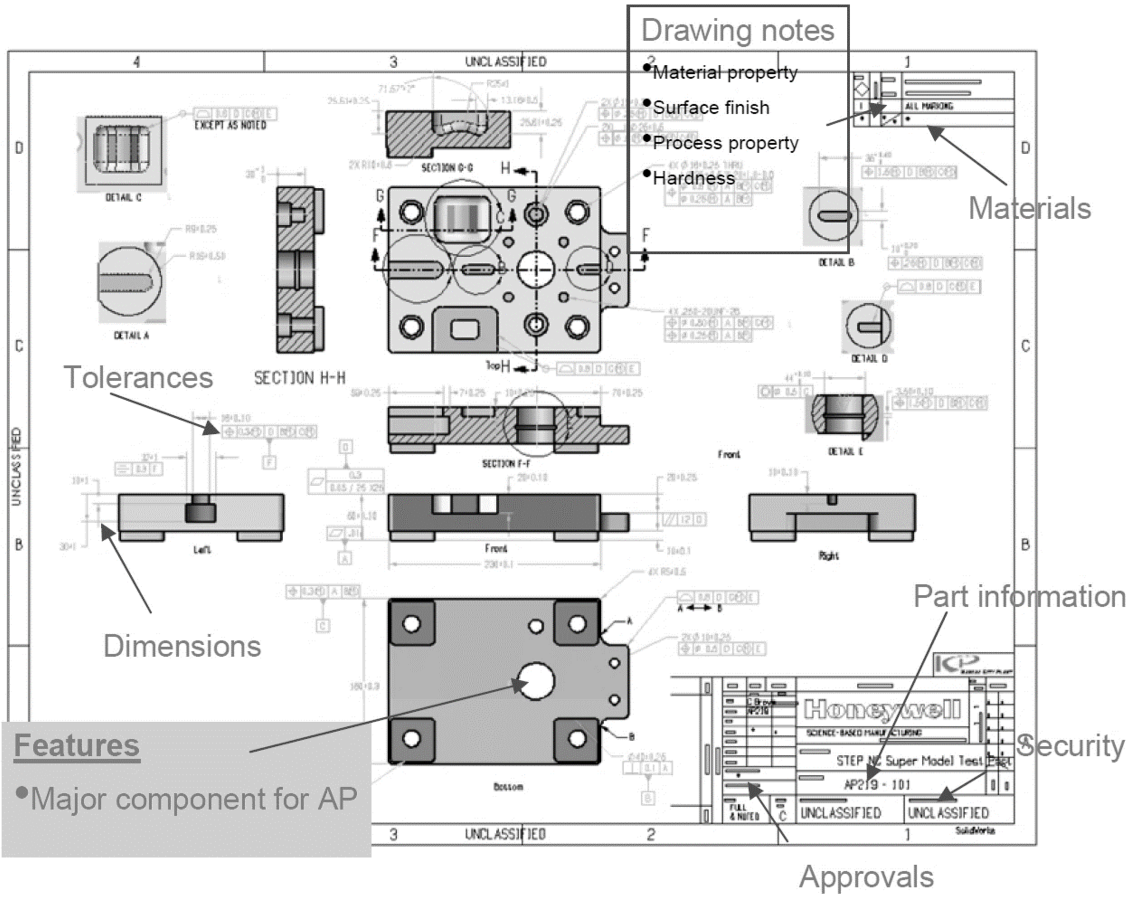


Figure 4-1: Examples of product data within STEP scope (SCRA 2006)

activities. Furthermore, it removes communication barriers among various computerised systems that have different proprietary formats (Mason 2002); hence, it is also an integration tool. STEP also provides the necessary means to design and implement feature-based manufacturing strategies as discussed during subsection 3.2.3. STEP has become an extensive repository of data models that satisfies different perspectives of a product within its lifecycle.

STEP was originally built upon initial graphics exchange specifications (IGES), which was updated in 1984 to form product data exchange specifications (PDES), (Kramer and Xu 2009). The PDES then become an international standardisation effort that ended with the first release of STEP as a draft document in 1988 that is then evolved over time until its first version was published as an international standard document in 1994 (Xu and Nee 2009). Today, it is still evolving as new product data, industrial application or processes may require a newly developed or modified STEP-based data model (Kramer and Xu 2009). Early implementations of STEP were successful in digitally exchanging product design data among distributed organisations.

STEP today can communicate not only the product information at the geometry level but also at the feature level and the manufacturing operation level. An illustrative scenario for clarifying how STEP can be deployed within the industry is to translate the system's proprietary formats to write a STEP output physical data file, which could be saved, shared, sent or read by another system via a pre-processing step. This mechanism enables product data exchange in the form of storing, transferring, accessing and archiving (ISO 1994a).

4.1.1. STEP application protocols and modularisation concept

When describing the STEP standard series architecture, it is necessary to introduce the application protocol (AP) concept and modularisation approach that has been followed by STEP committees. APs are subsets of the STEP framework that include information models required for a specific industrial application need or perspective. Application means any process that can produce or consume product data. APs are self-contained STEP modules that can be implemented and tested for conformance as a single unit.

The STEP parts that contain common information definitions that may be necessary for the development of different APs are known as STEP integrated resources (IR). Groups of information defined in an IR are also called resource constructs (RC); they are related to an aspect of product data. It should be noted that IRs are not sufficient alone to support information requirements of a specific application. RCs are divided globally into generic resources and application resources. A generic resource is independent of applications and reference only each other, while the application resources are application dependent and can reference the generic resources and add others RCs for use with similar applications. This modularisation approach allows information requirements of a new industrial application to be modelled directly by combining the already existing modules in a plug-and-play manner (Feeney 2002; Kramer and Xu 2009). The STEP architecture is still developing to enable software reuse strategy and to simplify the standard development and implementation process.

4.1.2. EXPRESS

ISO 10303-11 (ISO 1994b) is the formal STEP-data requirements specification language known as EXPRESS. It is used to define data entities, attributes, inheritance, relationships, rules and constraints. EXPRESS defines entities, application's objects, through focusing on its properties and constraints of an application domain. Object oriented terminologies such as data types, object instances are also applicable for

EXPRESS. EXPRESS can represent **simple**, **aggregation**, **named**, **constructed** and **generalised** data types. Table 4-1 shows the major categories of EXPRESS data types and the included data types in each category. **Integer**, **real**, **logical** and **Boolean** are examples of the simple data types. Aggregations are collections of many values of a given base data type which are the aggregation's elements. **Array**, **list**, **set** and **bag** are different aggregation data types in EXPRESS. The named data types are those types declared within formal specification. Named data types are of two kinds; they are **entity** data type and **defined** data type. The **entity** data type is considered as the modelled objects that its attributes take other entities or basic values. The **entity** can also have relations with other entities data type. **Defined** data type is used to add meaning and context for basic data types. **Enumerations** and **select** data types are called the constructed data types within EXPRESS. Finally, **generalised** data types are used to specify any generalisation required for the other data types. In other words, **generalised** data types are a generalisation of all the introduced data types such as when using aggregation data types instead of a specific aggregation type.

Attributes of an entity could be a subject for uniqueness or domain rules of EXPRESS. Uniqueness rule requires an attribute value of an instance to be unique among all instances population of a given entity data type. On the other hand, domain rules specified by **where** clauses allow a constraint to be defined on an individual or combined values of attributes for every entity instance of an entity data type. Attributes can also be declared as being **optional** within the specification based on the application requirements. A powerful modelling mechanism in EXPRESS is that **supertype/subtype** inheritance relations can be constrained, which allows for the specification of abstract supertypes. In addition, it allows for specifying an instance of supertype to be one of its subtypes, or to be of more than one of its subtypes using for example **ANDOR** or **AND** constraint. Functions within EXPRESS can operate a defined algorithm on its parameters to produce a single result value of a specific data type. Functions are a good point to

Table 4-1: EXPRESS data types classifications

Simple data types		Aggregation data types	Named data types	Constructed data types
Number	Logical	Set	Entity	Select
Integer	Boolean	List	TYPE	Enumeration
Real	String	Array		
	Binary	Bag		

apply generalised data types in its parameters for example. Express also includes some built-in functions to evaluate some mathematical expressions. Expressions can also be specified within EXPRESS; they are a combination of operators, operand and function calls to evaluate a value. There are arithmetic, logical, relational, membership and other operators that are defined to assist and extend the described EXPRESS capabilities as a data-requirement specification language.

EXPRESS-G, presented in ISO 10303-11 (ISO 1994d), is a STEP graphical tool that aids the understanding of modelled data requirements using EXPRESS. Although EXPRESS-G can represent all data requirements, it does not have a defined way to represent modelled rules and constraints involved within an EXPRESS data model. Figure 4-2 shows the symbols used in EXPRESS-G to represent different data types and entity relationships defined in the EXPRESS model. Figure 4-3 uses an example of data requirements represented in EXPRESS and its related EXPRESS-G diagram. The `person` entity represented in this example can be one of two subtypes; they are `male` and `female` entities. The `person` entity has four mandatory but two optional attributes. Hair type, birth date, first name and last name are a must attributes; age attribute is

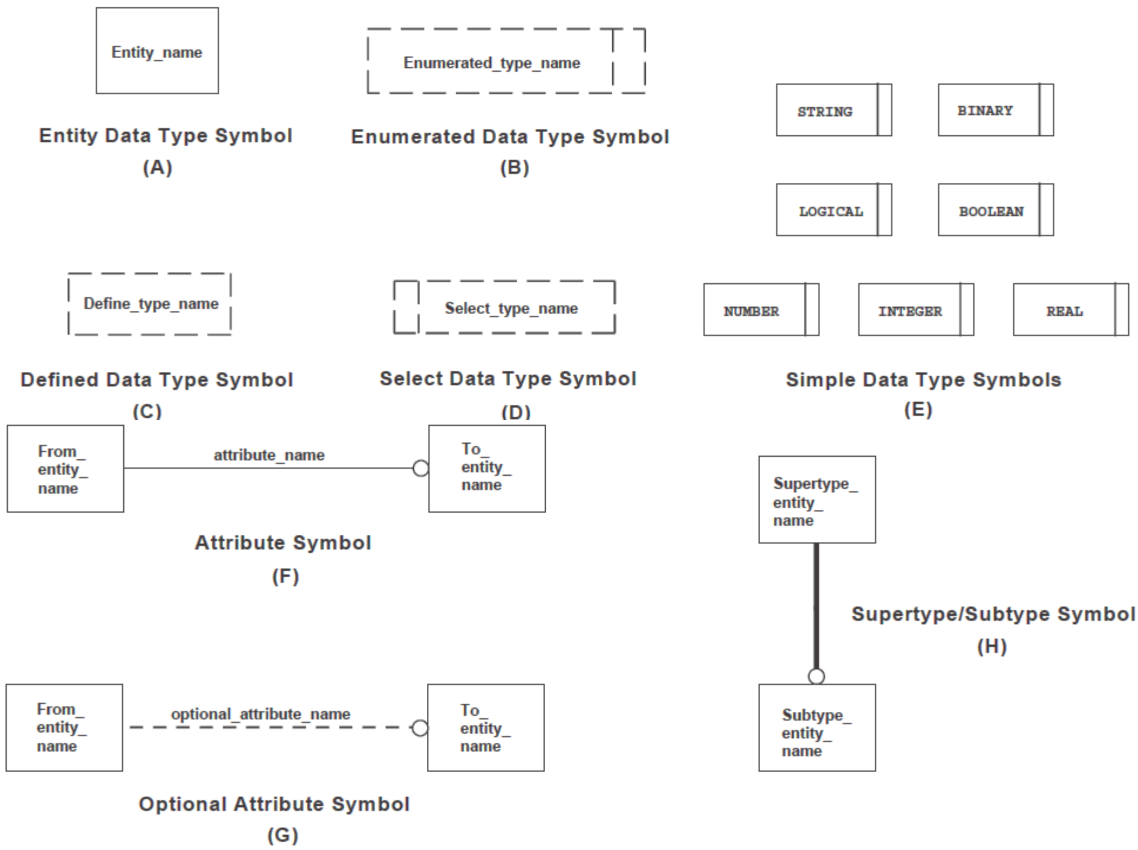


Figure 4-2: EXPRESS-G types and entity relations (McCaleb 1999)

```
TYPE hairType = ENUMERATION OF (blonde, brown,
                                black, red, white);
END_TYPE;

ENTITY person
   ABSTRACT SUPERTYPE OF (ONEOF(female, male));
   firstName : STRING;
   lastName : STRING;
   nickname : OPTIONAL STRING;
   birthDate : date;
   children : SET [0:?] OF person;
   hair : hairType;
DERIVE
   age : INTEGER := years(birthDate);
INVERSE
   parents : SET [0:2] OF person FOR children;
END_ENTITY;

ENTITY female SUBTYPE OF (person);
INVERSE
   husband : SET [0:1] OF male FOR wife;
END_ENTITY;

ENTITY male SUBTYPE OF (person);
   wife : OPTIONAL female;
END_ENTITY;
```

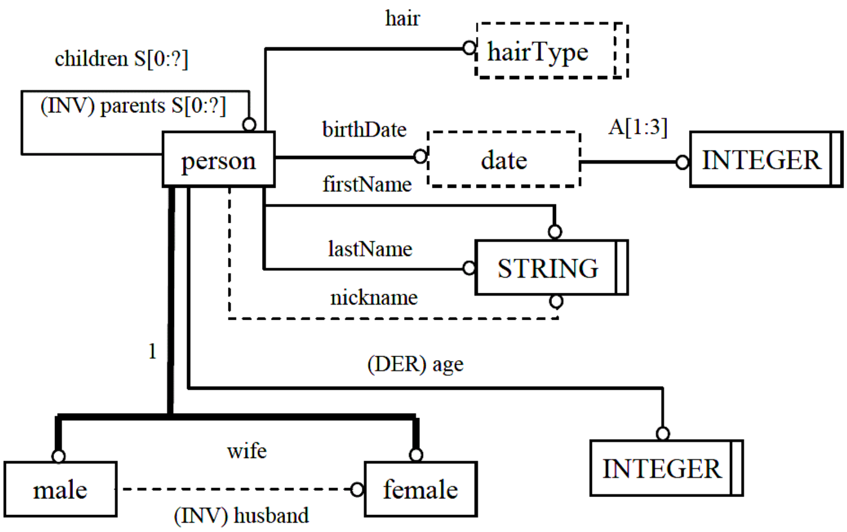


Figure 4-3: EXPRESS and EXPRESS-G illustrative example

derived, while nickname and children are optional attributes, as some persons may not have a nickname or children. The figure indicates that a person has one first name , last name, hair type and optionally a nickname while for a person having children, this could be from one to many children. The `male` entity could have a wife attribute that is represented by a `female` entity; this relation is inverted such that the `female` entity has a husband attribute that is represented as a `male` entity.

4.1.3. The application protocols development process

For a specific industrial application, the AP development process commences via a representation of the target application in terms of its functional requirements and information flow. These requirements and information identify the application scope and context. They are then documented as application activity models (AAM), which is based on IDEF0 which is a system analysis and visualisation tool. In the following stage, the detailed data requirements are identified and synthesised based on STEP specification methods. The following stage of the AP creation process is the documentation of its data requirements in the form of EXPRESS and EXPRESS-G models. These documents are known as AP's application reference model (ARM) or AP's application interpreted model (AIM). Both ARM and AIM are models of various information requirement and constraints represented by EXPRES and EXPRESS-G.

The main difference between both model views is that in ARM, the defined information model is constructed using common terminologies used by application experts, while in AIM, the defined model uses interpreted terminologies that exist in the STEP's IR to replace common field terms. While AIM could only be developed by STEP experts, ARM can be developed by field experts. AP's AIM is developed based on ARM via a mapping process. This mapping step is named as "interpretation" within the STEP AP development process. Interpretation may modify attributes' restrictions, constraints and relationships specified in the integrated resources definitions (ISO 1994a). Table 4-2 shows an example of the interpretation process in which the `workpiece` field term is interpreted in the mapping table as the `product_definition` term defined in ISO 10303-41 (ISO 1994d).

To put it all together, an AP is formally the final mapping or the interpretation of the IRs in order to satisfy information requirements of a target application. The final formal AP is documented in the form of its AIM model in addition to the related conformance testing specifications. Conformance testing is a check to verify and validate the different commercial applications used to manipulate STEP implemented files for a specific industrial scope. Conformance requirements to be satisfied by any industrial implementations are defined within its related AP. An abstract set of test cases called abstract test suites is specified for each AP. Test suits and abstract test method are the core tools for testing conformance of an industrial STEP implementation. Conformance

Table 4-2: ARM and AIM mapping example

Application element	AIM element	Source	Rules	Reference path
WORKPIECE	product_definition	10303-41		
its_id	product.id	10303-41		product_definition product_definition.formation -> product_definition_formation product_definition_formation.of_product -> product product.id
workpiece to material (as its_material)	PATH			product_definition <- product_definition_relationship.relating_product_definition {product_definition_relationship => product_definition_usage => make_from_usage_option} product_definition_relationship product_definition_relationship.related_product_definition -> product_definition characterized_product_definition = product_definition characterized_product_definition characterized_definition = characterized_product_definition characterized_definition <- material_designation.definitions[i] material_designation

testing scope is defined based on a declared conformance class by a tested implementation.

AIM models are the basis for any industrial implementations of an AP for data exchange or sharing purposes. STEP has the flexibility to map the EXPRESS model, within AIM, to different implementation methods based on industrial application requirements. Each implementation method in STEP specifies necessary mapping rules from the EXPRESS specification language to its defined structure. A physical text-based file is one STEP implementation methods used by computer systems to exchange EXPRESS-descried product information. This implementation method as a data exchange mechanism is defined in ISO 10303-21 (ISO 1994c). Figure 4-4 shows a part 21 physical file implementation of part of the example shown in Figure 4-3.

ISO 10303-28 (ISO 2007a) is an XML-based implementation method of EXPRESS defined data. XML representation addresses sharing of data structures within information systems especially via the Internet (Lu 2012). Consequently, part 28 makes STEP adaptable for the internet and web-based applications. It should be emphasised that EXPRESS is independent of the final intended representation form. This makes STEP able to cope with any innovations required by information technology developments in modern applications. In other words, final STEP implementation form is only dependent on the intended means of communication required by industrial application and available communication interfaces. Another example of EXPRESS implementation forms is standard data access interface (SDAI) that enables the sharing and archiving of EXPRESS-defined data within database systems.

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION((‘A FAMILY’),   /* description */
                      ‘3;1’);    /* implementation level */
FILE_NAME (‘ HESHAMS FAMILY’,    /* name */
           ’30-05-2016’,         /* time stamp */
           (‘ H MAHMOUD’),       /* author(s) */
           (‘UoB’),              /* organisation */
           ‘none’);              /* pre-processor version */
FILE_SCHEMA ((‘EXAMPLE’));
ENDSEC;
DATA;
#1 = MALE (‘HESHAM’, ‘MAHMOUD’, $, (01-01-1980), (#3,#4), .BLACK., #2);
#2 = FEMALE (‘MAY’, ‘MOHAMED’, $, (06-02-1987), (#3,#4), .BLACK.);
#3 = FEMALE (‘NOOR’, ‘MAHMOUD’, ‘NORY’, (02-05-2009), (), .BLACK., $);
#4 = MALE (‘Omar’, ‘MAHMOUD’, ‘MORO’, (10-10-2010), (), .BLACK., $);
ENDSEC;
END-ISO-10303-21;
```

Figure 4-4: Part 21 encoding of the data in Figure 4-3

4.1.4. STEP traditional and modified architecture

According to the described AP development process, traditional STEP standards architecture can be described as being divided into six different groups. Each group contains a number of standard parts. These groups are the description methods, implementation methods, IRs, APs, conformance testing and abstract test suites. Figure 4-5 graphically shows this STEP architecture with some examples of the included parts. STEP has since expanded its modularisation approach to a further extent because of the overlapping exist in the defined scope and data of different APs. This problem becomes complicated as the number of industrial applications covered by STEP increased. Definition of new modules in a modified STEP architecture has become necessary. Modularisation enables the reuse of the defined information models in addition to attaining the extensibility and interoperability principles among different APs. The new framework makes the AP development and implementing processes easier and shorter compared to the previous framework.

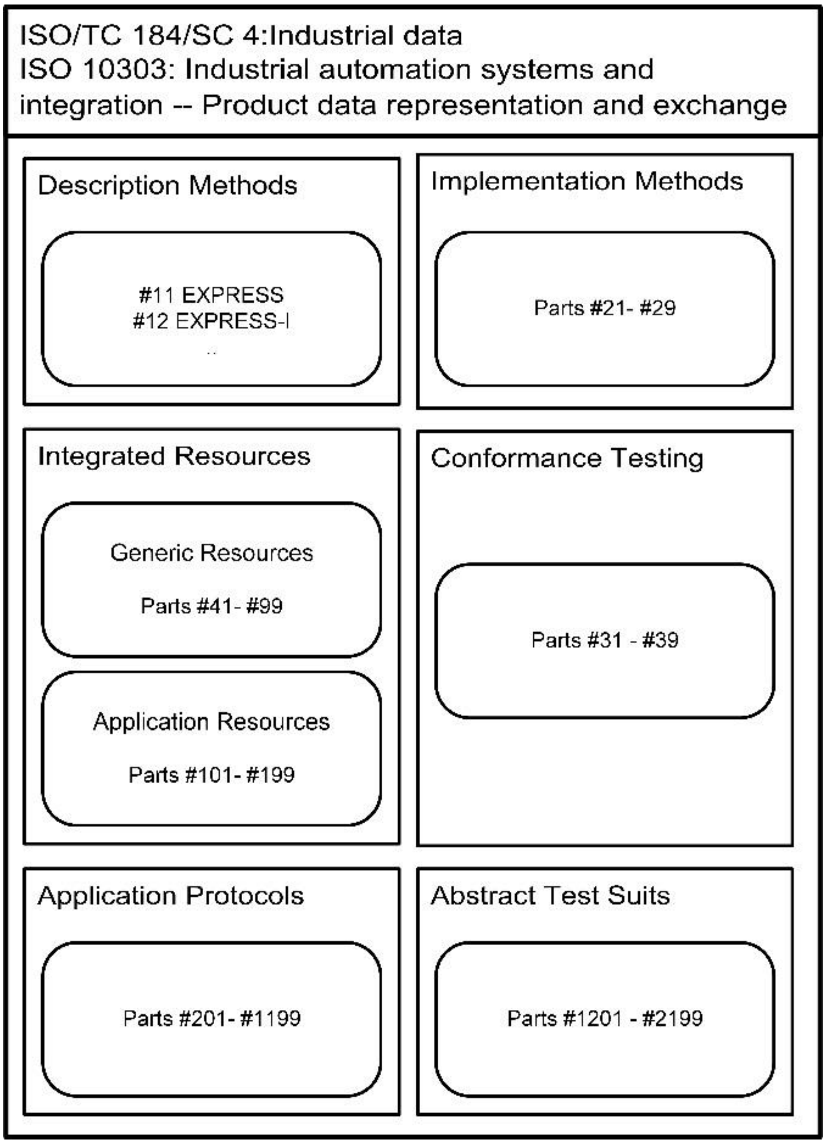


Figure 4-5: Traditional STEP architecture as described in ISO (1994a)

At first, application interpreted constructs (AICs) specified common subsets of an AIM that can be shared among different APs. Some AICs are then augmented by their related ARM models to define a shareable unit called application module (AM). AMs is also considered as being harmonised AICs across different information requirements and specification in addition to their interpretation. Figure 4-6 illustrates this modern AP modular and hierarchal structure, in which the AP is seen as a collection of reused AM components. Figure 4-7 puts this STEP modular structure into an overall conceptual organised framework of the overall STEP standard with some examples of part numbering systems and titles under each STEP conceptual component. The presented STEP modular structure in Figure 4-7 could be compared with the traditional framework

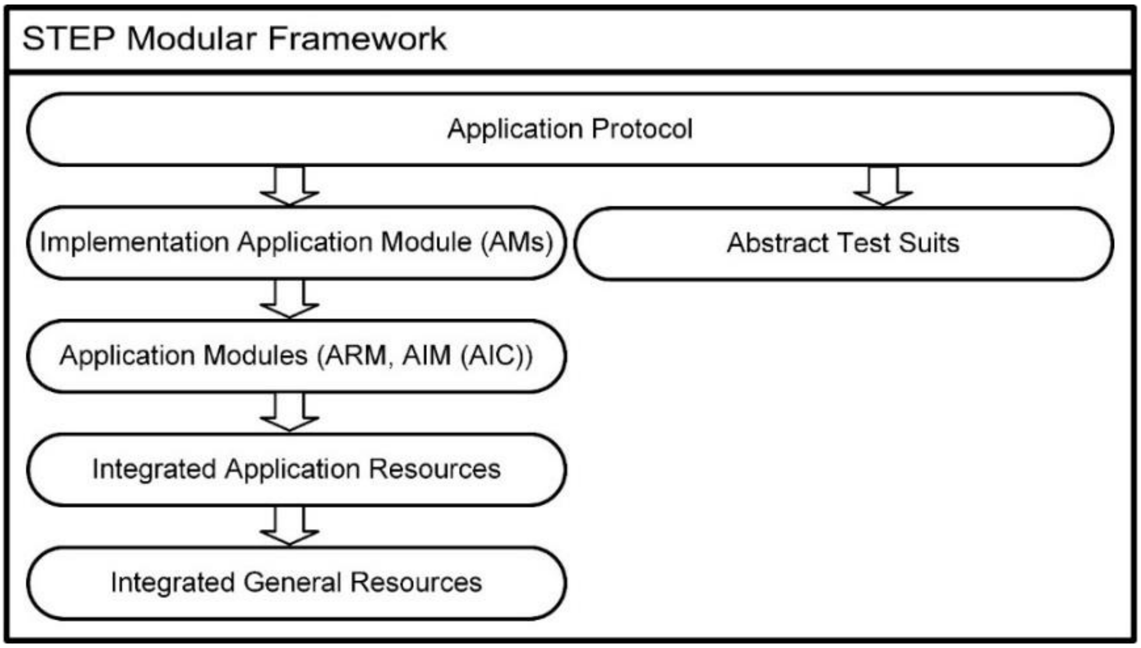


Figure 4-6: Modern modular STEP architecture

in Figure 4-5 to show how the modularisation approach has modified the STEP architecture.

The following subsections will present specific STEP parts and APs that are directly related to the defined research scope. This will include those parts implemented to enable CAD-CAD and CAD-CAM data exchange. In addition, STEP representation of process plans between CAM systems and controllers of computer numerical controlled (CNC) machines will be illustrated. The following subsections will also focus on current STEP data models used to represent measurement data to clarify their defined scope and consequently, their limitations.

4.1.5. STEP representation of design data

ISO 10303-203 (ISO 2011c) defines a standard for exchanging solid model data of both mechanical parts and assemblies; it is commonly exported from CAD systems. The AP203 document represents geometry and topology information, in addition to the different types of solid model representations. STEP solid model representations also suffered for many years from the absence of a method to communicate GD&T data, which is necessary for downstream applications. The STEP part 47 (ISO 1997), contains generic resource constructs to assist in the definition of GD&Ts data representation, but this part is not enough to represent the GD&T requirements necessary to satisfy industrial application needs.

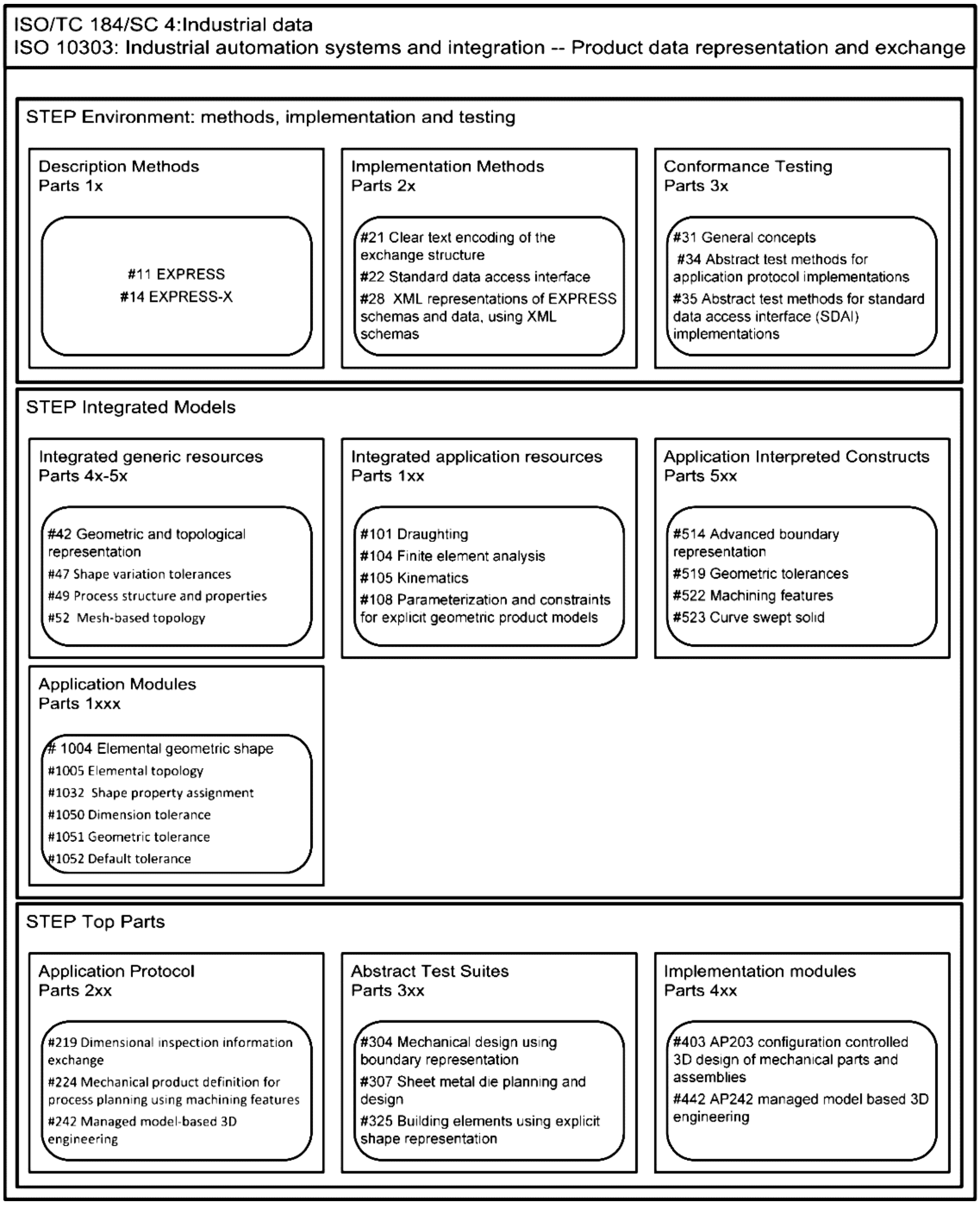


Figure 4-7: STEP framework conceptual classification

The publication of STEP AP214 (ISO 2010a), was a notable shift regarding this deficiency, as it extended the STEP AP203 by including additional information about colours, layers and GD&T. During 2011, and in its second edition, STEP AP203 followed the same route by augmenting its data model by adding GD&T information. A logical request for harmonising both versions of standardised product definition has been raised, as there are now two different APs within the STEP framework representing nearly the same data requirements in the same application context. In December 2014, this harmonisation process resulted in the publication of STEP AP242 (ISO 2014a), as reported by Lipman and Lubell (2015).

STEP AP242 not only aimed to harmonise AP203 and AP214, but also it added the representation context to the presentation rules, which were defined in ISO/DIS 16792 (2012) and ASME Y14.41 (2012) digital product definition standards, that enables the exchange of the GD&Ts information, in addition, presenting them graphically. The graphical presentation specified the rules for distributing and displaying GD&T annotations on the 3D solid models for better understanding and visualisation. Adopting these documents allowed not only the exchange of CAD data including GD&T among different CAD systems but also permitted the exchanged files to keep the visualisation aspect as it was originally created. Conceptually, AP242 is targeting the management of the 3D MBE and MBD perspectives, so its scope is wider than just representing PMI. Hence, it not only extends, but also replaced AP203 and AP214 in the modified STEP framework, but this is not yet the case for commercial applications.

AP242 was developed while considering downstream applications. The industrial implementation of AP242 will reduce the need for drawings that assists future MBD and MBE trends as discussed previously in section 3.1. Consideration of AP242 in the CAD industry has just started to be investigated; automation of CAM and CMM tasks has not yet been evaluated against the expected throughput of AP242 in their applications (Fischer *et al.* 2015).

One industrial limitation of the AP242 is the lack of coverage and support of its framework for manufacturing features (Boy *et al.* 2014), which is a critical requirement for enabling the use of measurement data for controlling machining processes. This highlights a need for its modification or harmonisation with AP224 that defines manufacturing features to allow feature-based activities. In addition, during an exploration of the STEP AP242 standard status, Feeney *et al.* (2015) and Qin *et al.* (2015) agreed that the exchange of the PMI semantics is still a limitation of the current tolerance standard data models. In this context, Sarigecili *et al.* (2014) interpreted the STEP-based GD&T specifications for tolerance analysis by using the OntoSTEP product model developed by Barbau *et al.* (2012) to add the necessary semantic definitions. As STEP is complex with many encoded rules and functionally implemented relations, the current implementations to publish and read STEP-based files may vary from one CAD system to another. This is against integration and/or interoperability philosophies and hinders the development of unified tools to use AP242 data for downstream applications.

As a proposed solution, the CAx implementation forum (CAx-IF), a group of software developers, has published recommended practice specifications for the implementation of AP242 within CAD systems. These data specifications aim to create a common way to implement complex STEP standards, which needs experts to traverse data within the implemented files. These recommendations are documented only in a human understandable format (Lipman and Lubell 2015). As an alternative way to handle this difficulty, NIST has focused on conformance testing of published neutral data formats from CAD software with respect to formal tolerancing standards (Lipman and Lubell 2015; Frechette *et al.* 2013).

4.1.6. STEP-NC machining information models

STEP-NC, ISO14649 (ISO 2003), is a mechanism of data exchange between CAD/CAM systems and controllers of CNC machine tools as illustrated in Figure 4-8. STEP–NC data models are naturally integrated within the STEP framework through using the EXPRESS specification language (KRAMER 2009). STEP-NC was developed with a clear objective to replace currently used G&M codes, ISO 6983 (ISO 2009), a programming method for CNC machines only representing axes movement of machine tools instead of representing the cutting operations and parameters. In addition, vendors of CNC machine tools usually provide their controllers with non-standardised extensions of the defined G&M codes. On the other hand, STEP-NC provides CNC controllers with a high-level information that enables bi-directional data exchange with different CAM systems (Brecher *et al.* 2006; Xu 2009).

ISO 14649 is made up of separate parts that were agreed to be published as an international standard as illustrated in Figure 4-9. ISO14649-1 (ISO 2003), introduces a conceptual framework of STEP-NC to represent the technological independent and dependent machining processes information. STEP-NC includes a suggested strategy for implementing its framework directly to CNC controllers via databases with SDAI or via data servers with EXPRESS-X queries in XML (ISO 2003). Nevertheless, STEP-NC has not been commercially implemented by vendors of machine tool controllers. Translators are used today for converting STEP-NC information into different controller tool path information. STEP AP238 (ISO 2006b), is tightly connected to the ISO 14649 standard series; AP238 is the AIM model of STEP-NC that is a one-to-one mapping of

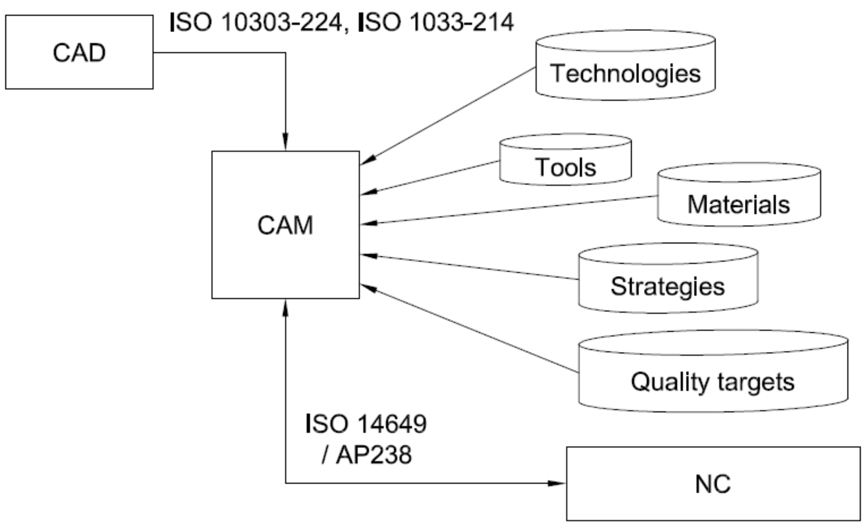


Figure 4-8: STEP-NC as a link between CAM systems and NC controllers

the ARM model defined in ISO 14649. AP238 relaxed some of the defined constraints in the original STEP-NC ARM data model during the interpretation process.

STEP-NC data flow uses geometry, manufacturing feature and manufacturing process data. Geometry data typically originates from CAD systems before being used in the construction of manufacturing features. Manufacturing features in STEP-NC are harmonised with manufacturing feature definitions in ISO10303-224 (ISO 2006a). Manufacturing features represent the removed volumes from the starting raw material until the final designed boundary is reached. Generally, some manufacturing features are related to the designed part final boundary; these features are linked to finishing

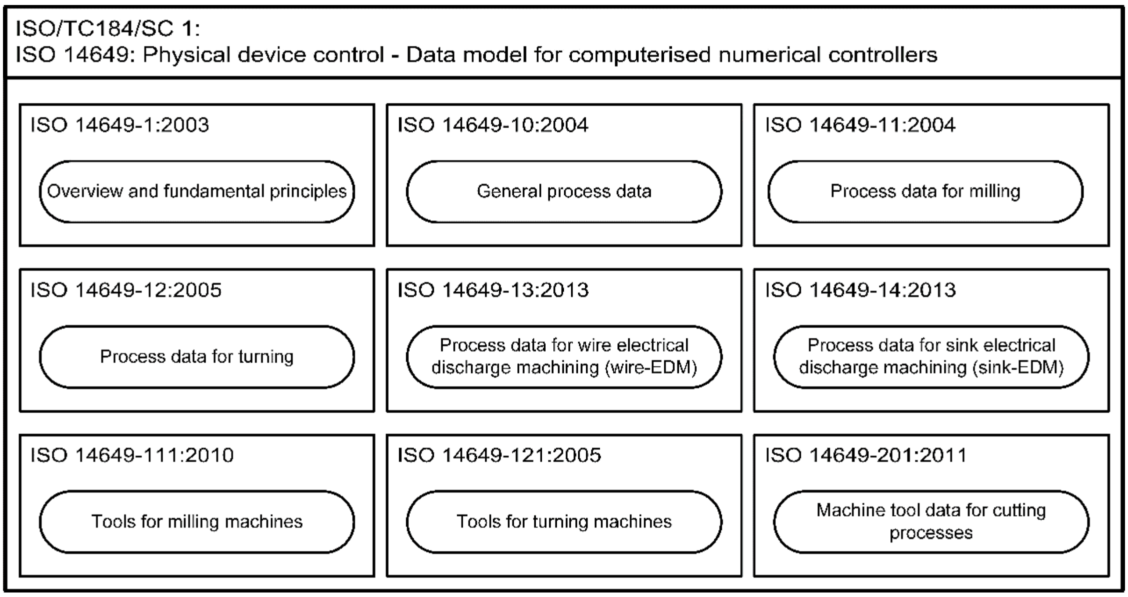


Figure 4-9: STEP-NC conceptual framework

machining operations. Other manufacturing features are not related to the part boundary as they are related to roughing operations; these can be seen as intermediate features. Both types of manufacturing feature typically originate within CAM systems automatically or manually through computerised interfaces. CAM systems also define their related manufacturing processes and technological parameters.

Figure 4-10 illustrates the overall STEP-NC structure through showing relations between top-level entities within its data model. A top-level `project` entity is the starting point for executing part programs. It has the `workplan` entity as one of its attributes. `Workplan` entity is formed of an ordered list of different `executable` entities. `Workingstep` abstract supertype entity, shown in Figure 4-10, is one subtype of `executable` entity. Other `executable` subtypes are the `NC_function` and the `program_structure`. `Workingstep` can be a `machining_workingstep`, `rapid_movement` or `touch_probing` subtypes; the latter is discussed in subsection 4.1.7 and Figure 4-11. `Machining_workingstep` defines machining data for one machining operation using one cutting tool and acting on a feature. Moreover, it is the mechanism used to associate the `machining_operation` entity to the `manufacturing_feature` entity created because of this operation, as they are both of its attributes. `Machining_operation` is the data container for the technological data of a `Machining_workingstep`. Examples of technological data are cutting tool, toolpath strategy, machining function, cutting depth, finishing allowance, cutting speed, feed rate, retract plane, safety plane, approach strategy and retract strategy. The final STEP-NC program structure can be constructed using `workplan, NC_function or program_structure` entities. `Program_structure` entity defines execution-flow control statements such as **parallel**, **if** or **while** statements.

4.1.7. STEP-NC part 16 for probing-based measurement data representation

Part 16 of STEP-NC (ISO 2004), is a non-published document that aims to integrate inspection process within the STEP-NC framework by providing a definition of measurement working-steps within manufacturing programs. Measurement data in part 16 is limited to contact probing and for basic measurement functionalities. Compared to other measurement standards, Part 16 provides a means to store inspection results to be used directly within the STEP framework without conversion (Brecher *et al.* 2006). This characteristic was used for enabling a feedback process to CAM and CNC controllers using OMI data. However, the feedback results could not change the defined

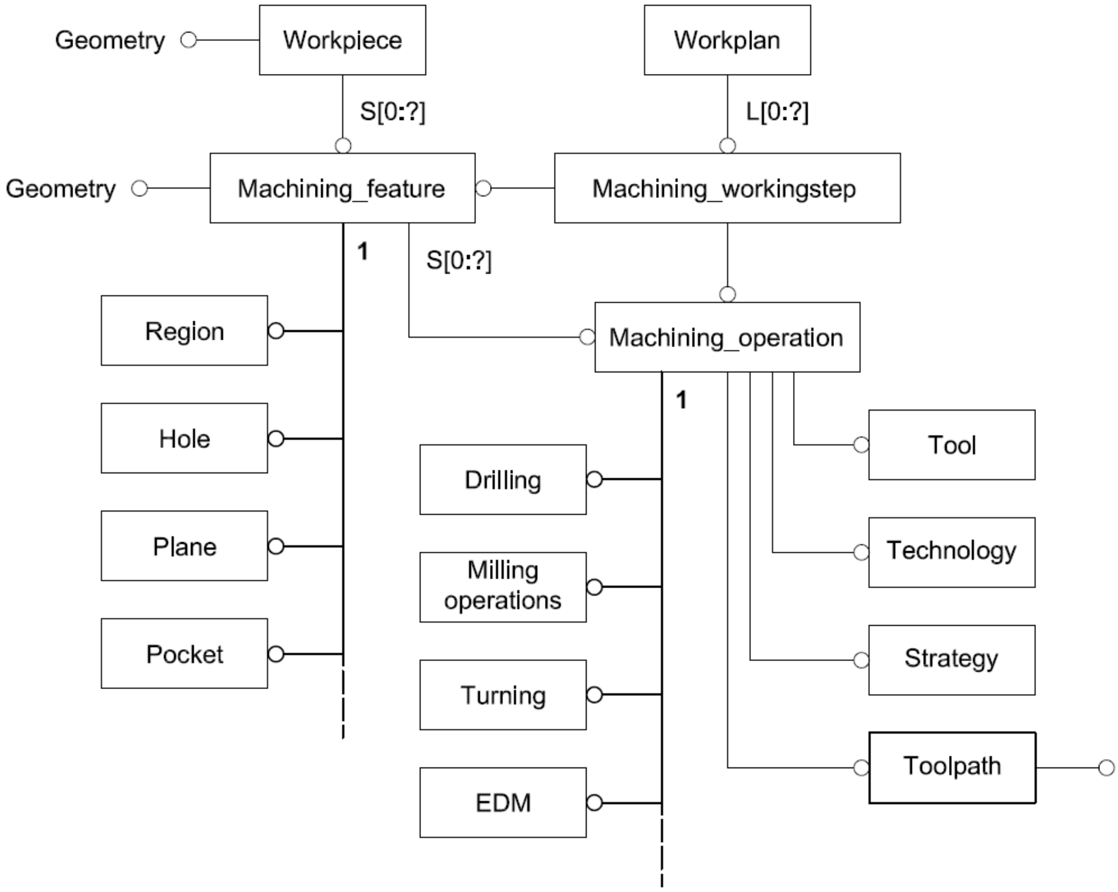


Figure 4-10: Overview of STEP-NC data model (ISO 2003)

geometry within the CAD/CAM database (Xu and Nee 2009; Newman *et al.* 2008; Zhao *et al.* 2008).

Figure 4-11 presents a conceptual framework of part 16 and its connecting entities to the STEP-NC data model. The `touch_probing` entity is defined in STEP-NC part 10 as a child of the `workingstep` abstract supertype entity. In Figure 4-11, `probing_workingstep` references both a `probing_operation` and one or more `inspection_item` entities. The `inspection_item` entity can define a linear or angular dimensional tolerance that applies to one `shape_select` entity through `toleranced_dimension_item`. It can also refer to a spanning dimension between many `shape_select`. Positional, orientation or runout tolerances are applied to a `shape_select` through the `tolerance_pose_item` entity. Shape tolerance is used to apply form tolerance to a `shape_select` and is represented by a `tolerance_shape_item` entity. `Shape_select` can be either a boundary representation entity, a machining feature or a set of their definitions.

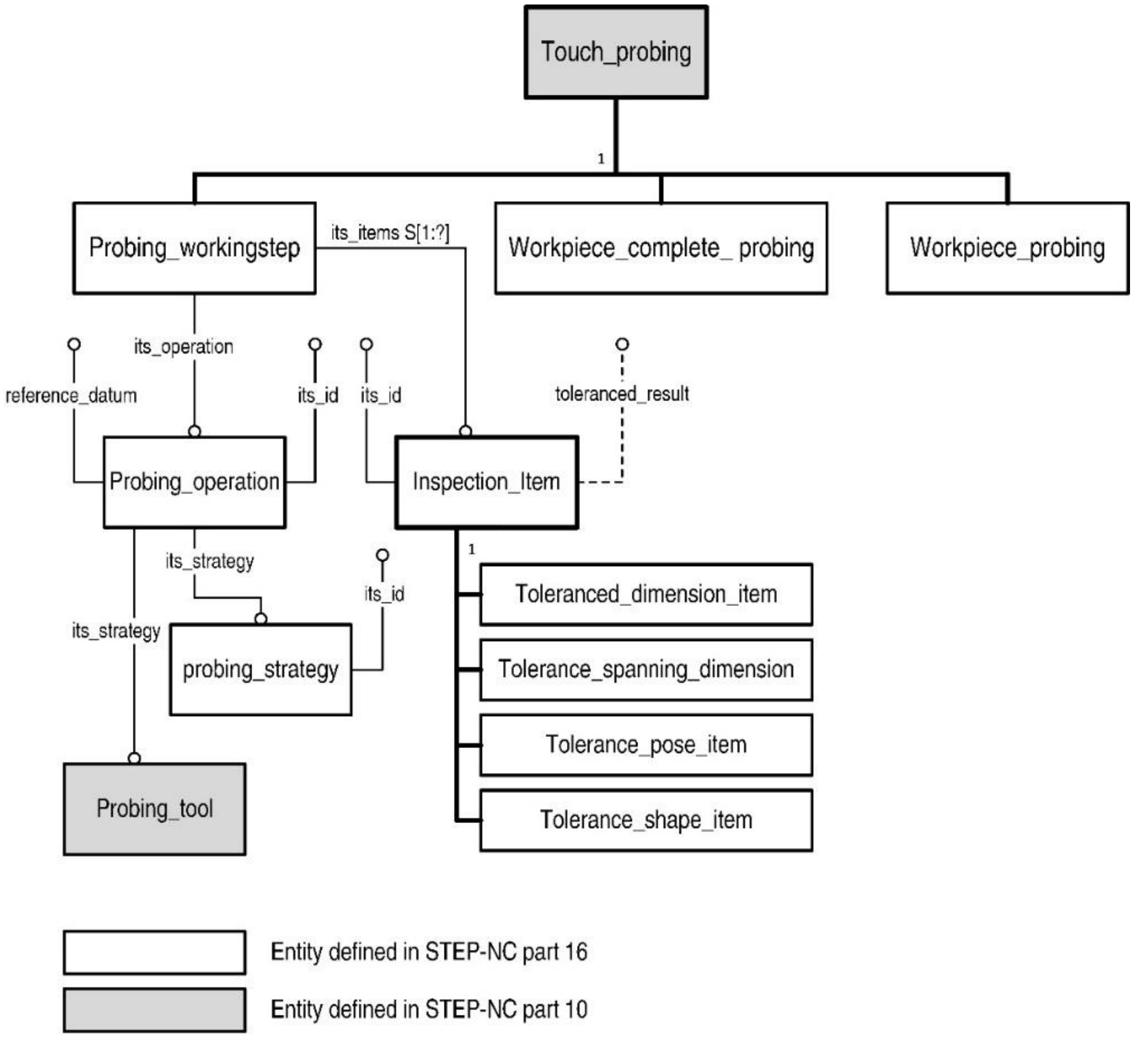


Figure 4-11: STEP-NC part 16 data model overview

Part 16 only references defined probing strategies in different CMM vendors' proprietary formats using a unique string attribute, as shown in Figure 4-11. Definition of inspection operations and strategies, how to measure, are out of the document scope (ISO 2004). In addition, other inspection methods rather than contact-based methods such as manual and optical measurement techniques are out of the defined scope of ISO14649-16 (ISO 2004). Part 16 needs to be extended to represent measurement operations used in coordinate metrology applications in a similar way to the other STEP-NC technological parts used to define turning and milling operations. In fact, part 16 is a primitive data model that represents limited tolerance information and inspection activities (Zhao *et al.* 2011a). Furthermore, Part 16 does not include any definition of inspection features that is necessary for the definition of various measurement tasks (Majstorovic *et al.* 2014; Zhao *et al.* 2009a; Zhao *et al.* 2011b). Inspection features are unique compared to both manufacturing and design features and need to be independently represented (Zhao *et al.* 2011b; Zhao *et al.* 2011a; SCRA 2006; Brecher *et al.* 2006); this will be discussed in section 5.2.

4.1.8. STEP AP219 for measurement analysis and reporting data representation

ISO10303-219 (ISO 2007b) is a part of the STEP framework that uses the IRs necessary for the definition of information requirements needed to represent the measurement results of solid parts or assemblies in addition to their evaluation circumstances. This AP contains fourteen different units of functionalities that serve its scope. The AP219 includes representation of measurement features that are harmonised with DMIS (Zhao *et al.* 2011a). On the other hand, its data model lacks the representation of measurement operations and strategies that specify how to measure a specific part entity (Majstorovic *et al.* 2014; Brecher *et al.* 2006; Zhao *et al.* 2011a; Xiaoping Zhao *et al.* 2006). The scope of the AP219 is oriented toward representing the necessary data for reporting the measurement results. Zhao *et al.* (2011a) criticised AP219 as it has not gained significant industry attention compared to DMIS and DML, as it does not have obvious advantages in storing measurement data. Zhao *et al.* (2011a) stressed that the AP 219 is the first and only standard effort trying to provide semantic associations between tolerances, measurement features, dimensional measurement results and their circumstance.

Figure 4-12 presents a conceptual diagram of the entities modelled within AP219. The starting point of the AP219 data model is the `dm_execution_input` entity that references `dm_program_run`, `part` and `dm_execution_result` entities as its attributes. The `dm_program_run` entity includes information about the environment within which execution of the related program has been performed. The `Part` entity represents measured part that is subjected to measurement program execution. This entity references a `shape` attribute that can take a set of `brep_shape_representation` or `shape_aspect` entities. Each `shape_aspect` entity is optionally referred to a `shape_element` entity, which can be substituted by any of its subtype entities such as direction, location, path and feature elements. Feature element can be a manufacturing feature or a defined measurement feature that is mapped from DMIS.

What is not clear here is the one to one cardinality starting from `dm_execution_input` entity up to `shape_element` entity that makes it difficult to attach the different results to different elements of shape unless there are many

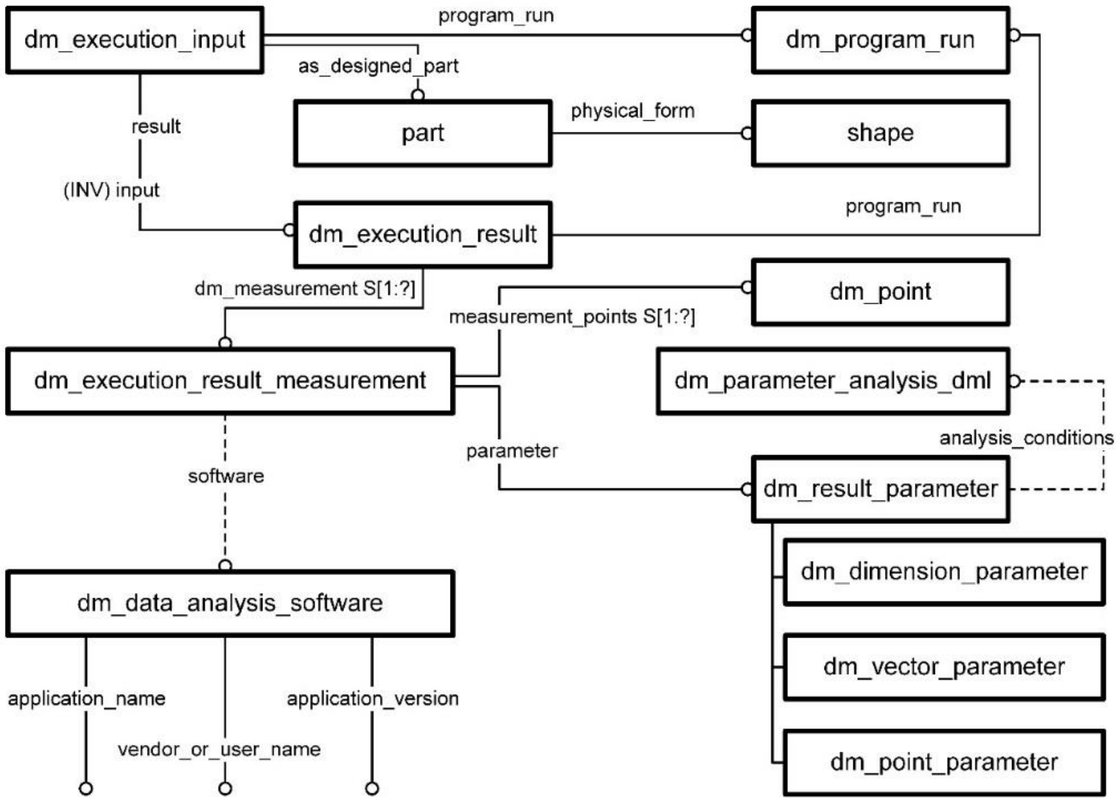


Figure 4-12: ISO10303-219 data model overview

`measurement_execution_input` entities in the file. The AP219 data model proposed a theoretical mechanism for connecting a `dm_feature` entity to a `manufacturing_featue` entity through the `Inspection_feature_relationship` entity. This mechanism needs to be reinvestigated to allow a collection of measurement features to be connected to a single manufacturing feature such as the case when checking a slot width. It could be argued that a `dmf_pattern` entity defined in AP219 could be used if many measurement features need to be linked to one manufacturing feature. In fact, the `dmf_pattern` entity may solve the modelling conflict, but sacrifice instead the semantic of the included measurement data as patterns semantically defined based on a one base feature that is repeated in different locations and not different measurement features collected together to serve a specific function such as common datums or compound hole features.

In short, the definition of the measurement feature and its relation to the manufacturing feature needs to be discussed thoroughly to represent in a better way the real measurement data requirements. ISO GPS recent modifications paved the way for theoretically understanding complex relations and requirements in this area, which if being based on, the measurement models become more representable for the measurement process real situations; this will be further investigated in details in the following section. Finally, in Figure 4-12, a `dm_execution_result` entity is the result data from the measurement program execution. This entity refers a set of a measurement point sets, where each set of points is related to a measured parameter through `dm_execution_result_measurement` entity. The measured parameter has an optional attribute to link it to the conditions used for its evaluation.

4.2. The ISO standardised series for Geometric product specification (GPS)

ISO GPS is a standard series that specifies workpiece characteristics in addition to requirements for their verification (ISO/TC213 2012; ISO 2015a). Its philosophy is to reduce variability that exists in the definition of products by providing an unambiguous means of communication between design and other downstream applications. Its strategy is to specify with minimal ambiguity possible target characteristics to be evaluated complemented by specifying the geometric features obtained from real workpiece or virtual surface non-ideal models. Origin of the ISO GPS strategy dates back to 1996 when three separate technical committees (TCs) for dimensional tolerancing, geometrical tolerancing, related metrology and surface texture standardisation have been combined into ISO/TC213.

Originally, there were two drivers for developing the ISO GPS system. The first was the need for a mathematical-based definition of GD&Ts. Mathematising the definitions of GD&Ts is aimed at facilitating the building of accurate and correct data models for computerised tolerancing and data exchange purposes (Srinivasan 1999); this, in addition, should help in standardising measurement analysis tools. The ISO GPS mathematical foundations are based on the modern mathematical theory for dimensioning and parameterisation in addition to classification of continuous symmetry groups as discussed by Srinivasan (2005), Srinivasan (2013) and Srinivasan (2015). The other driver was the emergence of modern coordinate and computational metrology systems and applications that require wider scope and tools compared to traditional GD&T specification and mathematical representation standards; for example ASME Y14.5, (ASME 2009), and Y14.5.1, (ASME 1994).

The adoption of ISO GPS tools within recent MBD standards could address closing the currently existing gap between the traditional GD&T standard definitions and the nature of the modern coordinate measurement applications. Methods of coordinate metrology have influenced the defined design specifications within the ISO GPS system through the introduction of new modifiers to cope with modern measurement trends (Srinivasan 2015). To clarify, Figure 4-13 illustrates an example of a traditional roundness specification; the figure also shows the effect of applied coordinate measurement methods on the variability of final evaluated or reported results. This is why the ISO GPS system provides richer varieties of new modifiers to enable the designer to exactly specify which type of feature is specified and hence how this feature could be derived or evaluated.

These newly defined modifiers provide the designer with necessary tools to specify what explicitly is mapped from different varieties of functional requirements. Morse and Srinivasan (2013) discussed for instance how new defined ISO GPS modifiers for size specification could help designers control the final part according to other functional requirements rather than correct assembly requirement. Edward *et al.* (2014) extended this discussion to clarify the degree of challenges that may face measurement practise because of new modifiers defined in the ISO GPS tolerance standards. One example of the introduced new modifiers can be shown in Figure 4-14 for a normal size specification. This figure shows that the specified size is a global size that is obtained from the

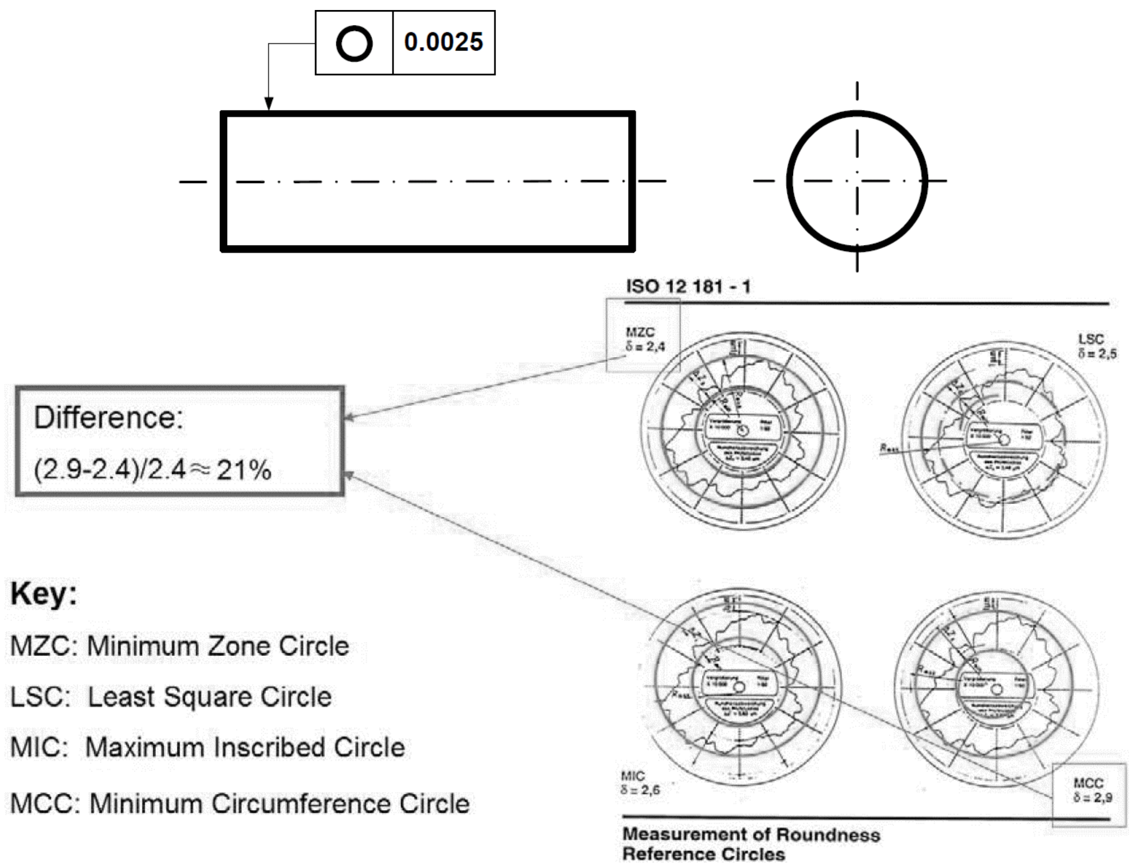


Figure 4-13: Variability of measurement results based on methods (Lu 2012)

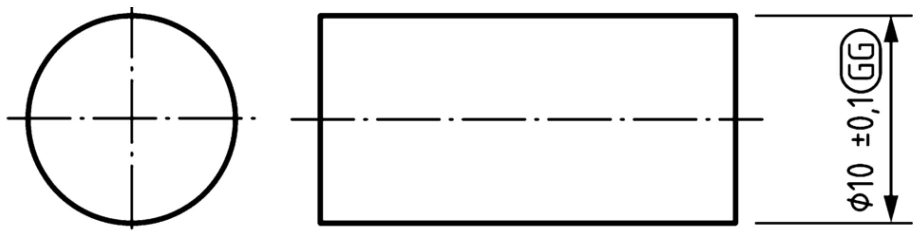


Figure 4-14: ISO GPS size tolerance modifier

measurement data using least-squares association criteria according to ISO/DIS 14405-1 (ISO 2013c).

Table 4-3 explores ISO GPS standard documents that are related to the specification of size, form, orientation, location and runout tolerances. These documents present necessary definitions, concepts and modifiers that explicitly convey a message from designer to downstream activities. Although these newly proposed standardised modifiers and symbols in ISO GPS system increase designer flexibility, they are not still applied within current CAD systems. The representation of these modifiers in CAD systems and the modelling of ISO GPS concepts in a computer interpretable format will greatly benefit the downstream applications. With regard to this work objective, the modelling of ISO GPS concepts in a computer interpretable format would also enable the overall goal of interoperable exchange of specifications of measurement process definitions.

4.2.1. ISO GPS master plan

ISO14638 (ISO 2015a) is a master plan that portrayed the overall ISO GPS system. The master plan represents the ISO GPS system in the form of a matrix model. This matrix model helps the users of ISO GPS standards to identify the extent and scope of each standard document based on its location within the matrix model. It also shows how the standard files are related to each other. The current scope of the matrix model includes nine different geometric properties of the workpiece. Table 4-4 documents the current ISO GPS matrix model with the nine geometrical properties within the scope of the ISO GPS system. The ISO GPS standard documents that are related to specific geometrical property form a category of standards. Table 4-5 shows, for example, the standards' category that is related to the geometric size property. Each category can be sub-divided into smaller chains of standards that represent specific elements of the geometrical property of this category. For example, the size category of standards can be subdivided to lower level standards to represent cylinder size and cone size elements of size property.

Table 4-3: Samples of ISO GPS documents related to design specifications

ISO 286-1:2010	Geometrical product specifications (GPS) - ISO code system for tolerances on linear sizes - Part 1: Basis of tolerances, deviations and fits
ISO 1101:2012 ISO 1101 Cor1:2013	Geometrical product specifications (GPS) - Geometrical tolerancing - Tolerances of form, orientation, location and run-out
ISO 2692:2006	Geometrical product specifications (GPS) - Geometrical tolerancing - Maximum material requirement (MMR), least material requirement (LMR) and reciprocity requirement (RPR)
ISO 5458:1998	Geometrical Product Specifications (GPS) - Geometrical tolerancing - Positional tolerancing
ISO 5459:2011	Geometrical product specifications (GPS) - Geometrical tolerancing - Datums and datum systems
ISO 10579:2010 ISO 10579 Cor 1:2011	Geometrical product specifications (GPS) - Dimensioning and tolerancing - Non-rigid parts
ISO 12180-1:2011	Geometrical product specifications (GPS) - Cylindricity - Part 1: Vocabulary and parameters of cylindrical form
ISO 12180-2:2011	Geometrical product specifications (GPS) - Cylindricity - Part 2: Specification operators
ISO 12181-1:2011	Geometrical product specifications (GPS) - Roundness - Part 1: Vocabulary and parameters of roundness
ISO 12181-2:2011	Geometrical product specifications (GPS) - Roundness - Part 2: Specification operators
ISO 12780-1:2011	Geometrical product specifications (GPS) - Straightness - Part 1: Vocabulary and parameters of straightness
ISO 12780-2:2011	Geometrical product specifications (GPS) - Straightness - Part 2: Specification operators
ISO 12781-1:2011	Geometrical product specifications (GPS) - Flatness - Part 1: Vocabulary and parameters of flatness
ISO 12781-2:2011	Geometrical product specifications (GPS) - Flatness -Part 2: Specification operators
ISO 14405-1:2013	Geometrical product specifications (GPS) - Dimensional tolerancing - Part 1: Linear sizes
ISO 14660-1:1999	Geometrical Product Specifications (GPS) - Geometrical features - Part 1: Genera terms and definitions
ISO 14660-2:1999	Geometrical Product Specifications (GPS) - Geometrical features - Part 2: Extracted median line of a cylinder and a cone, extracted median surface, local size of an extracted feature

Table 4-4: The ISO GPS geometric matrix model (ISO 2015a)

	Chain links						
	A	B	C	D	E	F	G
	Symbols and indications	Feature requirements	Feature properties	Conformance and non-conformance	Measurement	Measurement equipment	Calibration
Size							
Distance							
Form							
Orientation							
Location							
Run-out							
Profile surface texture							
Areal surface texture							
Surface imperfections							

In addition, each category of standards is divided into seven chain links that are related to a specific function in the specification or the verification of this geometric category. The seven chain links that map seven different specification or verification functions are as described in the column headings of Table 4-4. The matrix model may contain standards that specify requirements related to non-geometric properties. Currently, two non-geometric categories are defined within the ISO GPS system; they are manufacturing processes and machine elements categories.

Table 4-5: Example of related ISO GPS standards related to size specifications (ISO 2015a)

	Chain links						
	A	B	C	D	E	F	G
	Symbols and indications	Feature requirements	Feature properties	Conformance and non-conformance	Measurement	Measurement equipment	Calibration
Size	ISO 14405-1	ISO 14405-1	ISO 286-1	ISO/TR 16015	ISO 1938-1	ISO 463	ISO/TS 15530-3,
	ISO 286-1	ISO 286-1	ISO/TS 16610 series	ISO 14253 series		ISO 13385-1	ISO/TS 15530-4,
		ISO 286-2	ISO 14405-1			ISO 13385-2	ISO/TR 16015
						ISO 3650	ISO/TS 16610 series
						ISO/TR 16015	ISO 14253 series
						ISO/TS 23165	
						ISO 14253 series	
						ISO 10360 series	

Furthermore, ISO 14638 (ISO 2015a) classified the ISO GPS standard documents into fundamental, general and complementary standards. A fundamental standard defines rules and principles that apply to the entire ISO GPS matrix model, while a general document applies only to one or more geometrical characteristic categories and to one or more chain links. A complementary standard refers to non-geometric characteristic such as specific machining processes or machine elements. According to this standard, ISO 14638 (ISO 2015a) is a fundamental standard that affects all categories and chains within the ISO GPS matrix model. ISO (2011b), ISO (2011h) and ISO (2012c) documents are other three pillar fundamental standards that specify essential fundamental concepts, principles and rules valid for the creation, interpretation, and application of ISO GPS documents. As a default case, the principle of GPS standard hierarchy specifies that the rules and definitions on higher-level standard apply to all the lower-level standards unless otherwise specified in lower-level documents.

As a general guidance, some ISO GPS concepts are oriented to the organisation of and definition of scope and limits of each rule defined in a specific ISO GPS document type. Other principles have also been oriented to standardise used terminologies for both characteristics and features. New concepts such as total uncertainty, operators, operations and duality principle have been defined. Furthermore, a mathematical foundation for GD&T and datum definitions has been introduced. According to ISO (2011j), these fundamental documents are not intended for industrial use but are rather aimed to serve as a road map for the standardisation for industry and software makers. The following subsections are oriented to focus on the crucial theoretical GPS foundations that are related to the aim and scope of this research.

4.2.2. Geometric features

Many ISO GPS documents were oriented to focus on the classification of geometric features and their different definitions. ISO (2000), ISO (2011i), ISO (2011h) and ISO (2014b) are those ISO GPS standards that included the terms, definitions, classifications and rules related to the geometric feature to serve both specification and verification functionalities. The feature principle, as introduced in ISO (2011b), states that a workpiece is made of a number of features limited by identified boundaries. This concept also states that unless otherwise specified a GPS specification applies to one entire feature or one relation between features. In fact, features information is essential for all manufacturing activities. As discussed in subsection 4.1.6, design and manufacturing environments use well-defined features that serve the design and manufacturing objectives. Conversely, the entry point of metrology requires the use of real surfaces created by the various machining technologies including their random and systematic errors, which are different from designed nominal features or the defined removed volumes affected by machining processes.

Recognising the interrelations between different feature perspectives is crucial for the correct identification of proper feature representation in a specific application context. It is also important when the status of one feature perspective could affect decisions related to the formation or the definition of another feature perspective. Features can exist in three separate but related environments; they are a specification, a workpiece and an inspection environments. The nature of these environments is either virtual or real. Virtual environment includes both nominal surface model and skin model; the first represents virtually the ideal geometry definition, while the later model defines virtually the non-ideal geometry. Discrete model is obtained from the skin model by an extraction. Sampled model, on the other hand, is obtained from the real workpiece surface through physical extraction through a measurement device. Based on these defined environments, geometric features can be seen as nominal, real, discrete and sampled. Nominal features refer to features defined during the design stage for satisfying necessary functional requirements. Real features are those features created during the manufacturing processes and deviate because of included systematic and random errors from the designed features. Discrete and sampled features are those features obtained by extraction of the real virtual or physical workpiece. Figure 4-15 shows the different representations of the workpiece and geometric features as presented in the ISO GPS system.

Geometric features can be points, curves, surfaces, volumes or a set of these to form a compound or a coupled features. ISO GPS further grouped ideal features that are invariant under the same DoF(s) into seven different invariance classes. Situation features are features of type point, line, plane or helix; they can be used independently or together to locate and orient geometric features in 3D. Features of the same invariant class have the same situation feature type. Table 4-6 illustrates those seven different invariance classes and the related situation feature for each class. The seven invariant classes are crucial for the specification and datum identification tasks as only the variant DoF(s) are those that need to be specified and locked by datum systems as described in ISO (2011a).

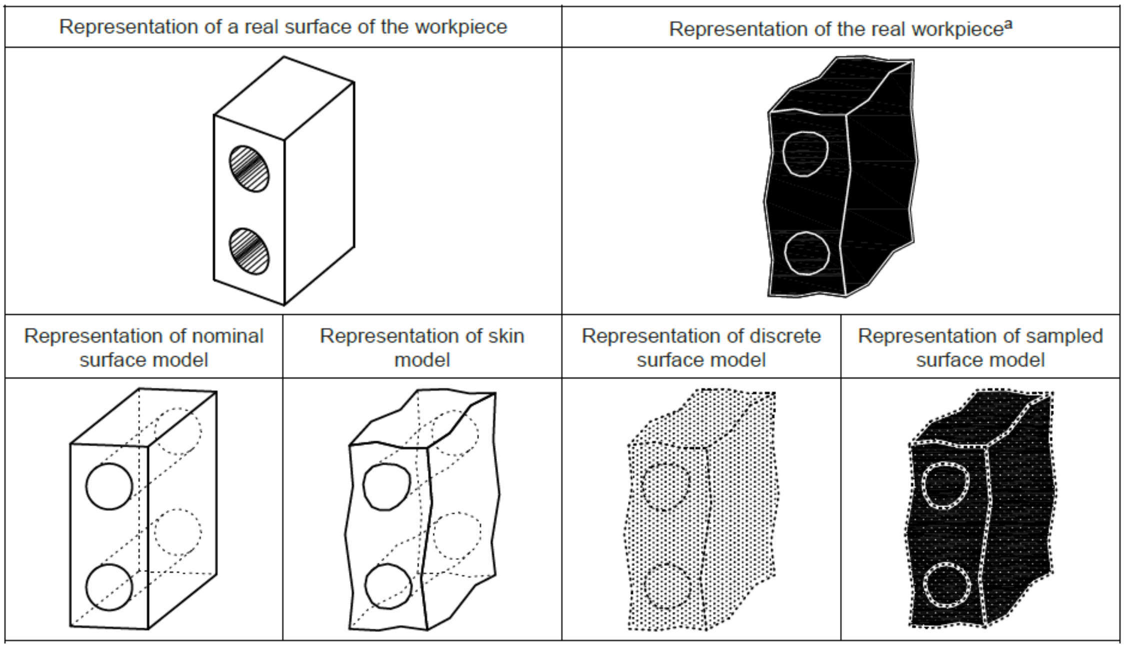
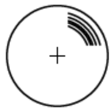
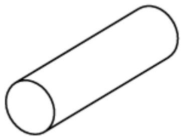
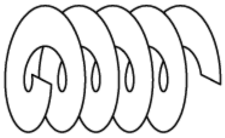
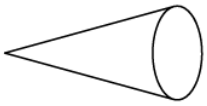
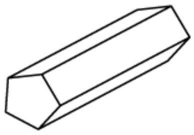


Figure 4-15: Virtual and real geometric features in ISO GPS (ISO 2011i)

Geometric features can also be classified based on their nature as being integral or derived. Integral features are those surfaces that are an integral part of the part final boundary. In contrast, the derived features are the features that are not an integral part of the final workpiece boundary but are derived based on integral features. The situation, offset, median, congruent and projected features are all types of a derived feature. Geometric features can also be seen from the extent point of view as being infinite, complete finite or restricted feature. To cope with the coordinate metrology perspective, ISO GPS also defined intermediate geometric features that are obtained through different operations from the real physical workpiece.

The intermediate features are extracted, associated, filtered or constructed features. Extraction features represent point clouds obtained from the part real surface through specified measurement procedures. Filtered features are obtained by the removal of some unnecessary geometric information from extracted data. Associated features are ideal-form geometric features that are attached to the non-ideal extracted entities. Conversely, constructed features are those ideal features defined based on previously defined or measured ideal features. Enabling features are those that are used to enable the construction activities to obtain for example, intersection curves and areas between constructing elements.

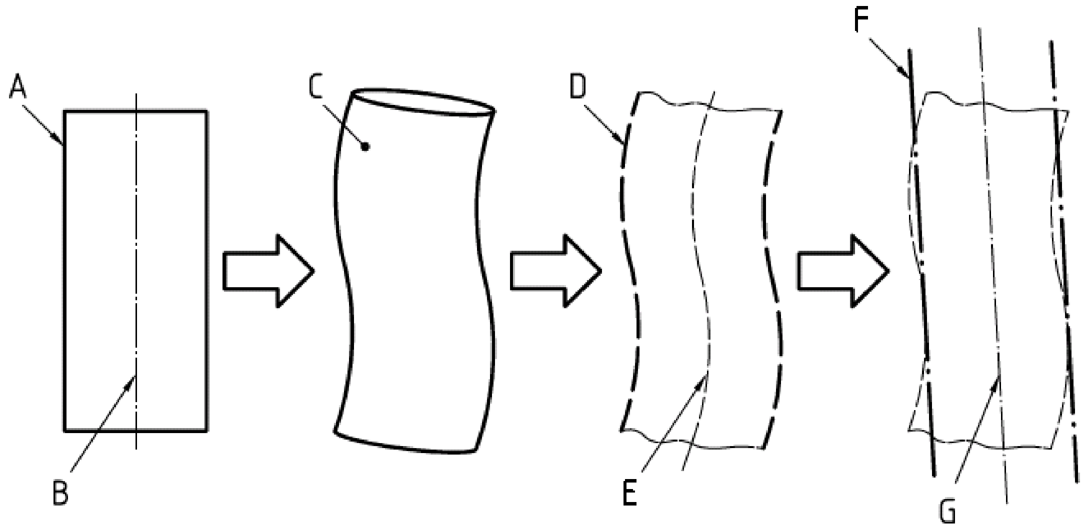
Table 4-6: Invariance classes of geometric features (ISO 2011a)

Invariance class	Unconstrained degrees of freedom	Illustration	Situation features	Example of types of surfaces
Spherical	3 rotations around a point		Point	Sphere
Planar	1 rotation perpendicular to the plane and 2 translations along 2 lines of the plane		Plane	Plane
Cylindrical	1 translation and 1 rotation around a straight line		Straight line	Cylinder
Helical	Combination of 1 translation and 1 rotation around a single straight line		Straight line[a]	Helical surface with a basis of involute to a circle
Revolute	1 rotation around a straight line		Straight line Point	Cone Torus
Prismatic	1 translation along a line of a plane		Plane Straight line	Pentagonal prism
Complex	None		Plane Straight line Point	Bezier surface based on an unstructured cloud of points in space

[a] Helical surfaces as such are not considered in this International Standard. They are regarded as cylindrical surfaces because, in most functional cases where helical surfaces (threads, helical slopes, endless screws, etc.) are involved, the combined rotation and translation of the helix is not needed for datum purposes. In these cases, the pitch cylindrical surface is used for the datum; the major or minor cylindrical surface can also be considered and specified. Natively, the situation feature of a feature belonging to a helical invariance class is a helix, but in this International Standard we consider only its axis.

It is worth stressing that the intermediate features are non-existent before the start of the coordinate measurement process. Consequently, they are not represented by any standard data model for CAD and CAM data exchange. Hence, there is a need to consider these feature types as a means to define measurement entities for the data exchange of measurement process. Some of these feature definitions can be illustrated by referring to Figure 4-16; it should be noted that these features are important for both specifications and measurement activities as stated in ISO (2011i) and ISO (2000).

The described intermediate features help in constructing both the deviated or reference features when considering the measurement evaluation of a specific characteristic. Deviated features are those associated features to the extracted and filtered feature unrelated to the datum constraints. However, the reference features are



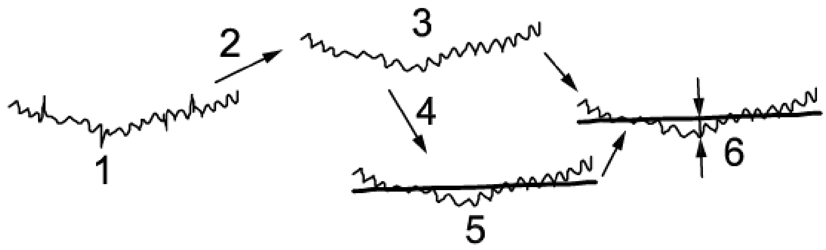
A.. Nominal integrated feature, B.. Nominal derived feature, C.. Real feature, D.. Extracted integral feature, E.. Extracted derived feature, F.. Associated Integral feature, and G.. Associated derived feature

Figure 4-16: ISO GPS geometric features

those situation features of tolerance zone of related characteristic. It is obtained by the association of ideal features while respecting the constraints imposed by datum feature or other features in relation to the characterised feature. The characteristic deviation is defined as the evaluated maximum distance between the deviated and the reference element; this is what is compared finally with allowed tolerance for checking the actual feature conformance to a specific specification (ISO 2015c, 2011h). Figure 4-17 shows an example of the evaluation of a basic characteristic using both deviated and referenced features definitions. This distance should be evaluated normal to the reference element as illustrated in Figure 4-18.

4.2.3. Characteristics and conditions

ISO (2015c), ISO (2011h) and ISO (2011j) are the ISO GPS standards that present the definition, terms and rules for geometric characteristics and their specification. As a general principle, each GPS specification should be fulfilled independently of any other specification unless otherwise specified. A specification is a sort of a condition that is imposed on a geometric characteristic. This condition involves limit values and some defined binary relation that defines a mathematical expression. Defined limits can be of dimensional or zone types within which the non-ideal evaluated characteristic should exist. Geometric characteristic is related to geometrical properties of characterised features. It can target one single feature or a group of features and can be related or unrelated to a datum system.



Key

1 non-ideal feature
2 filtration
3 deviated feature
4 association
5 reference feature
6 basic characteristic

Figure 4-17: Deviated and referenced features for measurement evaluation (ISO 2011j)

GPS specification can control both micro and macro geometrical properties that can be quantified. This could mean a basic geometrical characteristic that is an intrinsic characteristic or a situation characteristic. The intrinsic characteristic controls size parameters of a single feature of size (FoS), while the situation characteristic controls location or orientation between two different features. Shape characteristics such as form can also be seen as a situation characteristic of type linear distance between the deviated feature and the reference feature as in Figure 4-17. Individual characteristics target a single geometric property on one or more feature of a workpiece while population characteristic is a statistic defined by many characteristic values for a population of workpieces. A characteristic can be local or global based on if its evaluation result is unique or not across the feature. A two-point diameter is a local characteristic along a specified circular section while the least square associated diameter of a specific circular cross section is considered a global characteristic.

A local or global individual characteristic can be evaluated directly from single evaluation or can be calculated from a collection of a set of local direct evaluations. A characteristic can be evaluated by quantifying the signed or unsigned deviation between

Figure 4-18: Distance based measurement evaluation (ISO 2011j)

the ideal specification value and the real one. The real value of dimensional limit characteristics is obtained using the intrinsic or situation characteristics of associated features to extracted feature data. Alternatively, in the case of zone type limits, the real value is the minimum intrinsic characteristic of an associated ideal feature that representing zone containing the actual feature. Mathematically, ISO GPS system evaluates deviation of zone-based specifications as the maximum distance between each point of deviated feature to reference feature. This maximum distance as a quantifying function on the variation curve of all local deviation is known as mathematical operators. In fact, the reference feature is an associated ideal feature; consequently, the association criteria and the association constraints used for its definition can vary the final evaluated characteristic values. Figure 4-19, Figure 4-20 and Figure 4-21 clarify how measurement planner selections during the processing of intermediate features could affect final reported evaluated results. This is why it is of great importance to plan these in ahead in a unified manner to eliminate such variabilities.

4.2.4. Operator and operation

ISO (2012c) and ISO (2011h) introduced the terms related to operators and operations concepts. Operator is a set of operations that are applied in a specified order where each operation is a defined set of actions defined with a relation with a specific type of feature. Operators and operations can be defined for either specification or verification activities. A specification operator contains the specified operations required to obtain a feature from the real part surface, while the verification operator describes the implemented operations to obtain a feature from real surface via measurement apparatus. It should be noted that for a specific feature, the perfect verification operator is the one that is mirroring its specification operator ideally. This is not a necessary case as a simplified verification operator with intentional deviation from the specification operator is allowed according to the metrology independence concept. As a basic ISO

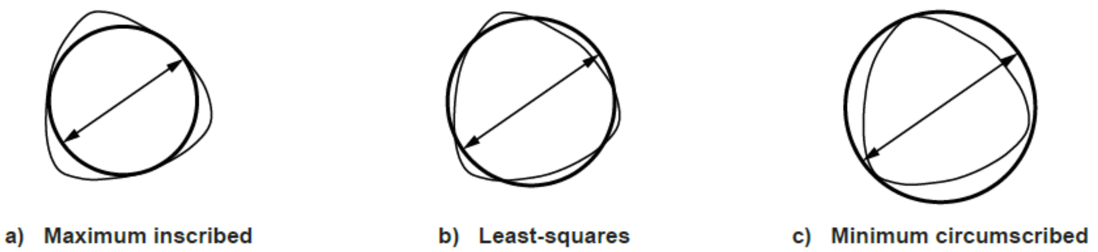


Figure 4-19: The effect of association criteria on characteristic evaluation

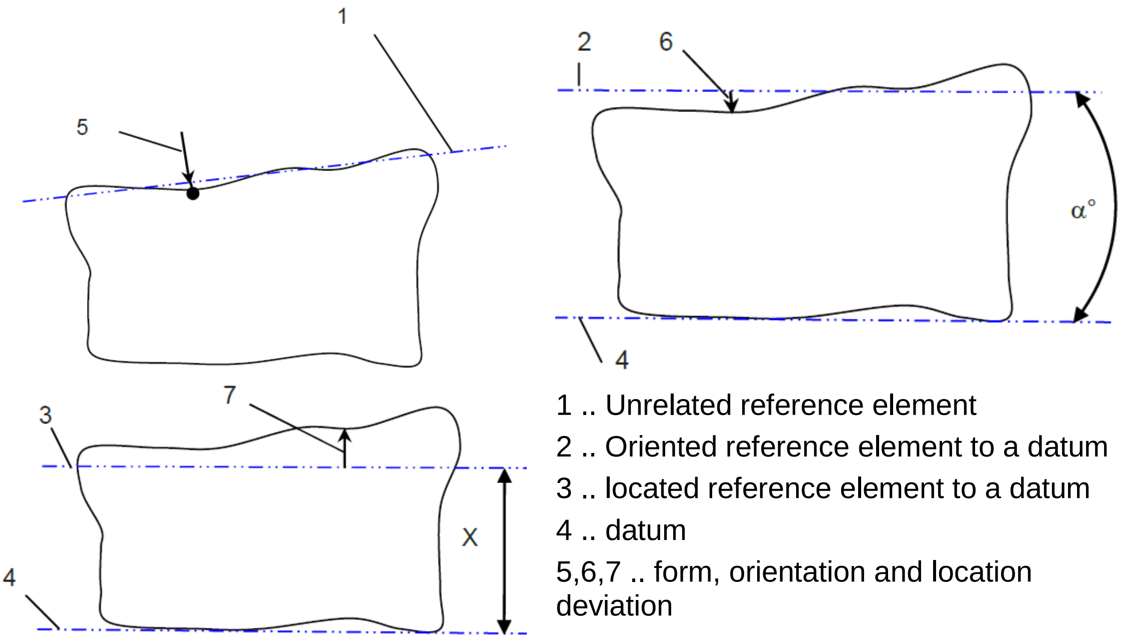


Figure 4-20: Association constraints based on the characteristic specification type

GPS tenant, the realisation of GPS specification is independent of the GPS specification itself.

Features obtained via skin or discrete models by specification operators are specification features, while those obtained from skin, discrete, sampled or real models via verification operator are called verification features. The actual specification operator found in technical part documentations can be indicated implicitly when default values apply or explicitly if a special specification modifier is used. In fact, ISO GPS default principle affirms that a modifier is only added to a GPS specification to alert the default criteria of this specification that is naturally inferred if there is no specification indicated. Figure 3-7 shows how the operation concept fits within the ISO GPS conceptual approach.

Feature operations can be classified as partitioning, extraction, filtration, association, collection, construction and evaluation operations. Extraction operation is a defined measurement procedure to obtain point clouds from the real part surface as an approximate representation of it. ISO (2010b) discuss generally defined extraction

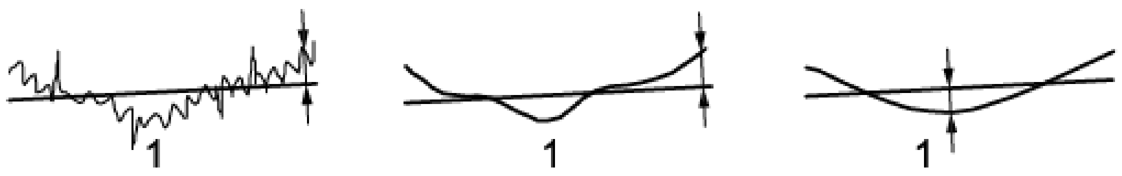


Figure 4-21: The effect of filter nesting index on the final form characteristic value

strategies for measurement applications, as described in Figure 3-17 and Table 3-1. Partitioning operation is used to divide the collected data into those groups of data related to distinct surface features required for specific measurement evaluation; this can mean partitioning a feature out of extracted data of a part or partitioning a restricted part out of a complete part. According to the ISO/TC213 roadmap for 2015, partitioning standard will take the series number of ISO 18183 and is expected to be published during spring 2017. Filtration operation is used to separate some unnecessary geometric information from a specific measurement activity perspective. ISO16610 (ISO 2015b) is a collection of standards that specifies filtration operations basics and different filters types and parameters. There are no yet defined ISO GPS standards to specify the rest of features operations. Association operation attaches an ideal form geometric feature to the non-ideal extracted data. Construction operation is used to derive feature definition based on other previously defined, measured or constructed features. Collection operations are used to collect different geometrical entities together to serve as a group for a specific measurement objective. Indeed, evaluation operation is not a direct feature operation as it does not result in a feature type but, on the other hand, it is used to identify the value of a specific characteristic based on deviated and reference features. As discussed in Figure 4-19, Figure 4-20 and Figure 4-21, it is a main shortcoming to limit the planning activity to extraction operation definitions, as characteristic evaluation greatly depends on the other analysis operations related to the intermediate features.

4.2.5. Duality principle

The Duality principle describes this ideal case in which the actual measurement implementation is seen as a mirror of the actual specification operations (Cristofolini *et al.* 2009). In other words, the duality principle stipulates that verification activities should follow specification operators and that measurement and specification operations should be related in both theory and practise (Srinivasan 2015). However, this should not compromise the principle of verification independence, as specification operator is defined independently of any measurement procedures or equipment and the verification operation is realised independent of the specification itself (ISO 2011b). Nielsen (2013) clarified the both concepts by stating that two ISO GPS perspectives should ideally map each other, but they are not necessarily the same. Figure 4-22 clarifies the discussed duality principle graphically.

ISO GPS theoretically has the potential to be the base of a data model for representing measurement plans, which could be formulate based on rich definitions of

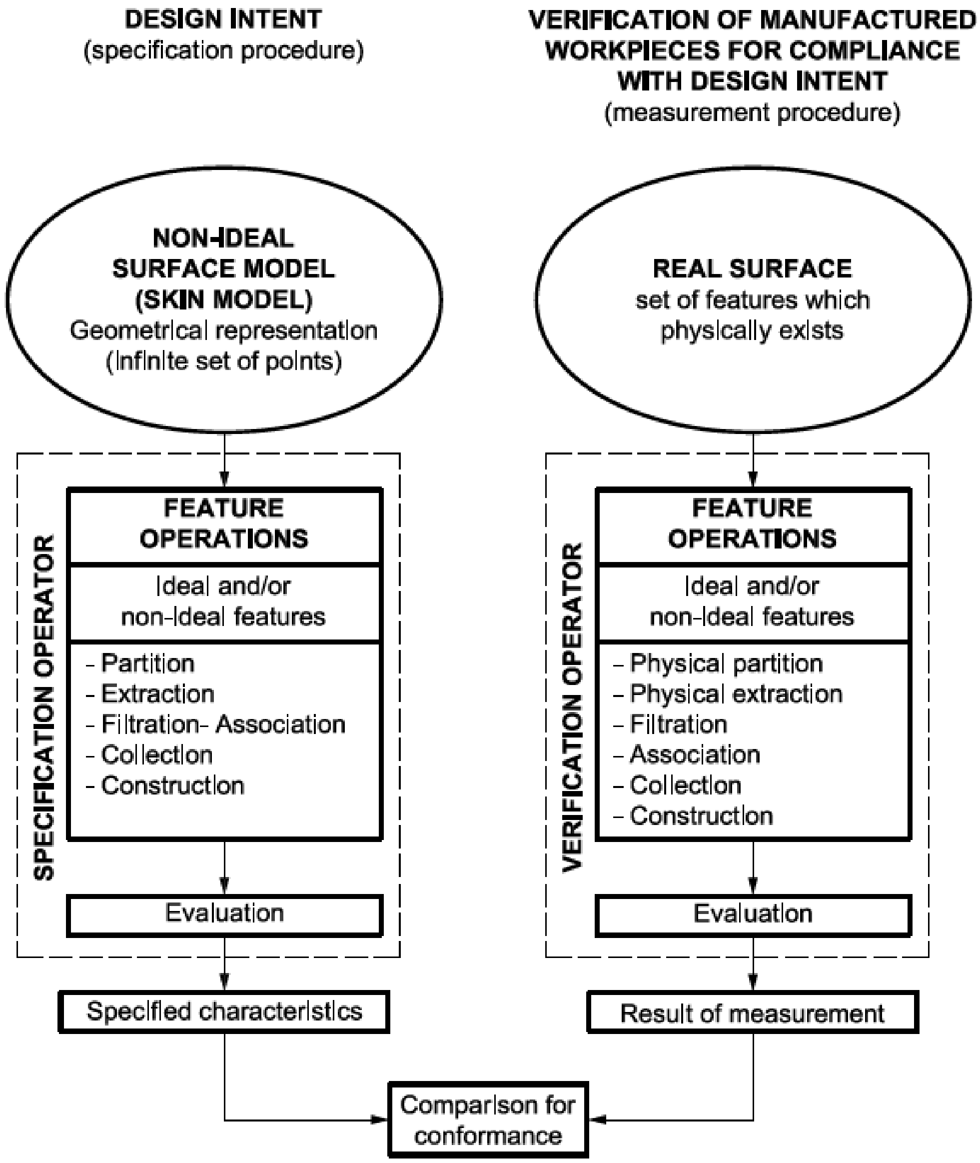


Figure 4-22: ISO GPS duality principle (ISO 2011h)

features and operations presented within ISO GPS. The measurement operations specifically could be represented based on presented ISO GPS theoretical foundations. This research supports the view that practically the lack of knowledge required by a designer, to specify exactly how the part is to be verified, hinders the designer's practical ability to provide complete and accurate GPS specification operators. This makes the realisation of the duality principle being an ideal case depending on the availability of the measurement knowledge that in some cases may not be related to the targeted functional requirements considered by the designer. Instead, it is assumed that the measurement planner should still have the role to complete the measurement operator based on his/her own knowledge and experience to match the standardised design specifications. In other words, designers need only specify variations allowed for real workpiece surface or any related integral surface according to stated functional requirements. These surfaces are actually created during manufacturing; they also affect intended final functional performance of final products. On the other hand, relating the intermediate feature types to the real controlled surface, specified by the designer, using necessary tools that match the functional needs should be the responsibility of measurement process planner. This agrees with the basic characteristic definition, (ISO 25378:2011), which does not include the definition of intermediate features obtained by feature operations. It is not realistic, without additional inspection knowledge, to burden designers by setting the specification for intermediate feature types that do not exist in reality until measurement process begins, which is a future vision of ISO GPS. This confirms the need for developing standards or best practise recommendations of how to apply the feature measurement operations to obtain the intermediate features and evaluate specified characteristics in a way that matched the intended functional need.

4.2.6. Total uncertainty and duality principle

ISO GPS is aimed to provide a tool for unambiguously specify design requirement in order to reduce overall uncertainties within the product lifecycle. ISO GPS presented the total uncertainty philosophy as being the sum of every uncertainty element that exists, starting from stating functional requirements and ending with stating measurement results. This total uncertainty concept and its components and their interrelations are illustrated in Figure 4-23. The total uncertainty is broadly divided into correlation and compliance uncertainties. The correlation uncertainty represents the difference between actual specification operator and intended function of the workpiece. The compliance uncertainty resulted from specification ambiguity and measurement uncertainty. According to this approach, the measurement uncertainty is not limited only to variabilities that exist in measurement process implementation, but also to the differences between the actual specification and actual verification operators (Humienny 2009); this last component is named as the method uncertainty that represents the deviation from the duality principle definition. This means that low measurement uncertainty alone is not enough, but also measuring what exactly the specification declared is also important. This also means carrying out the measurement process with low uncertainty is of little value if the ambiguity in the function requirements description or in the design specification or both is large.

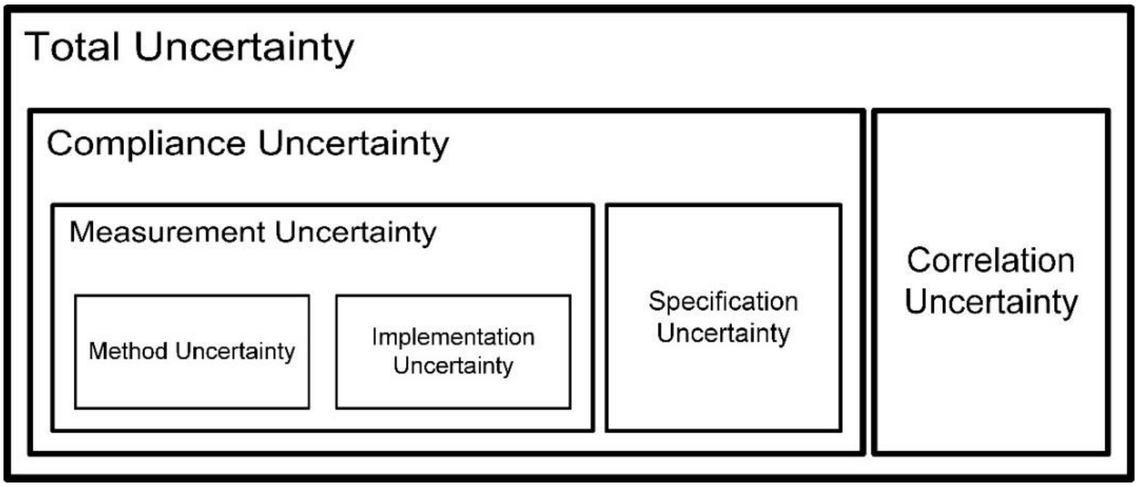


Figure 4-23: ISO GPS uncertainties and their interrelations

4.3. Dimensional measurement interface (DMIS) standard

The DMIS language is the basis of a large proportion of commercial software for CMM today (Hocken and Pereira 2012). The DMIS language is developed and maintained by dimensional metrology standards consortium (DMSC). ISO 22093 (ISO 2010c) defines DMIS as a neutral language for communication between Information systems and CMMs. It is an execution language for part measurement programs and provides definitions of metrology data such as measurement features, sensors, resources, results and tolerance. Savio *et al.* (2014) see DMIS as a mean of achieving interoperability that is limited to be between CMMs only among other measuring equipment. DMIS can work as an input program format that encoded instruction necessary for CMMs to perform measurement actions. CMM controllers interpreted high-level DMIS instructions into low-level machine motions. Besides, DMIS can also work as a reporting format for output results from measurement equipment (Yaoyao Zhao *et al.* 2012; Horsfall 2007).

In fact, a measurement equipment interfaces with each other directly through DMIS or through pre-processor and post-processor steps for considering equipment's native data format. DMIS measurement program can be created manually or via the assistance of CAD systems and computerised tools. Yaoyao Zhao *et al.* (2012) agreed that DMIS is the only standard that combines measurement features and operation data as a language for controlling CMMs. Nevertheless, Zhao *et al.* (2012) stressed on its limitation as it only related to specific types of resources; this resulted from the fact that DMIS definition of measurement operations and features are achieved only at the program level, which is strongly linked to specific measurement equipment. NIST has a testing platform for providing a certificate of DMIS compliance for commercial software for ensuring measurement program interoperability (NIST 2001).

Moreover, DIMS is not integrated into the STEP extensively developed data models (Brecher *et al.* 2006). DMIS does not use any of the previously discussed STEP tools and it is an independent programming language for controlling CMMs with its independent specifications. It also does not have direct access to the STEP-based data defined within CAD and CAM systems. Brecher *et al.* (2006) added that DMIS lacks the manufacturing context, features, and process plans, as it is not feature based if compared to STEP-NC, for example. In addition, Brecher *et al.* (2006) supported the conceptual approach of this research in that integrating inspection data within the STEP framework is the only way to obtain seamless data exchange without neglecting any activity context, which will eliminate any unnecessary conversion and inconsistencies. Ali (2005) considered another limitation of DMIS which is that it does not provide a complete description of inspected part as it does not contain any geometric modelling capabilities. Kramer *et al.* (1998) clarify some ambiguity in the DMIS specification that may lead to some assumptions such as the relation between nominal feature definition and its related actual is one-to-one, which is not the case in reality. Compared to DMIS, STEP can provide a consolidated framework that could enhance the CAD-Inspection communications and automation (Fischer *et al.* 2015).

4.4. Quality information framework (QIF) standards

Building upon the DMIS standardised specifications, DMSC developed QIF as an integrated set of American national standard institute (ANSI) standards to facilitate interoperability of manufacturing quality data. Version two of QIF was accepted as an ANSI standard during late 2014. The second QIF version included eight different parts, the first two of which are focusing on the QIF overview and basic concepts in addition to QIF shareable data. The other six parts describe the information models of different six application areas of the quality information. ANSI (2014a) is the QIF library; it is a central information model that can be used by any of other application-oriented data model. ANSI (2014b) provides a representation of an MBD of a designed product that forms the input for measurement planning. The following parts are information models for quality plans, resources, rules, results and statistics. The first version of the standard, published in 2013, was limited only to the measurement plans and results information models as independent applications. All of the QIF information models is written and represented by the XML schema definition language (XSDL). Characteristics in the QIF standard is harmonised with ASME Y14.5 and QIF measurement features definitions is mapped from the DMIS features. Figure 4-24 portrays the overall QIF roadmap.

In fact, compared to all discussed inspection standards, the unique contribution of QIF is that it defines a mechanism to represent measurement rules when being defined. Logically, a standard is valueless without its industrial adoption and acceptance (Srinivasan 2008). The adoption prospect of any standard increases, if it represents the field rules and knowledge (Chiabert *et al.* 2013; Ricci *et al.* 2013a). On the other hand, QIF shares some limitations of DMIS as it also lacks the context of both manufacturing features and processes. QIF could be seen as the data exchange models that uses DMIS as its implementation method (Morse *et al.* 2016). The proposed QIF data flow begins prior to the measurement execution via the generation of the QIF MBD and based on this a quality plan that includes what to inspect is constructed. The how-to-measure data are derived based on the available resources and the measurement knowledge represented as a set of rules. Post measurement execution, the measurement results are represented and can be used by the following statistical process control activity.

QIF is based on its own designed MBD data structure for conveying the part geometry, features and tolerances data (ANSI 2014a, b). This requires conversion and

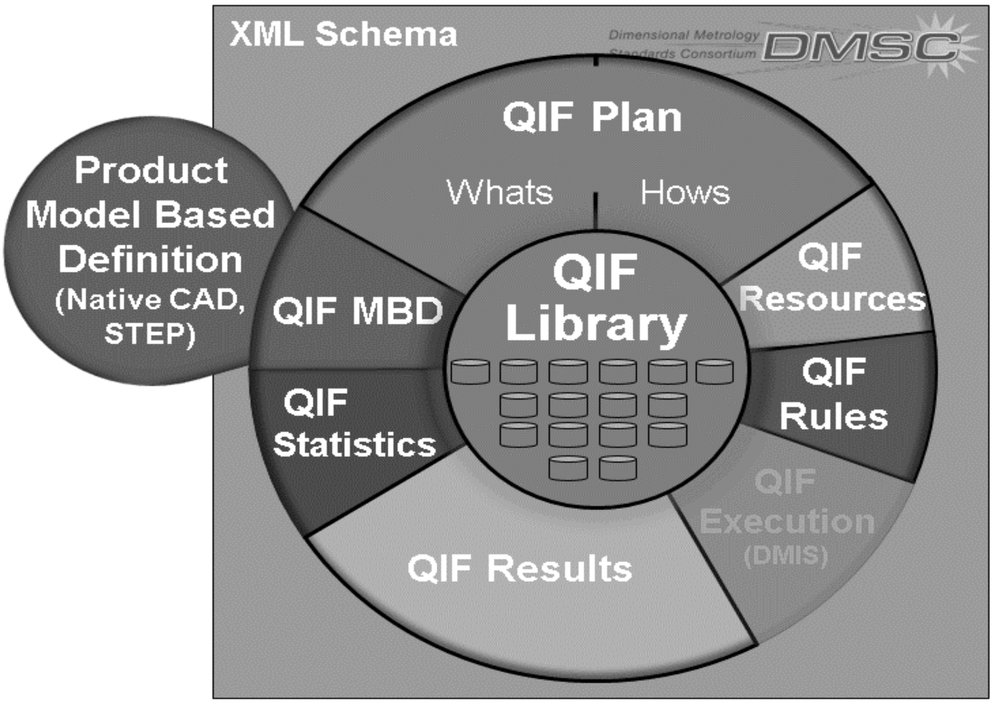


Figure 4-24: Complete QIF roadmap (ANSI 2014a)

translation processes from both design and measurement execution stages to the QIF format. This has been confirmed by the QIF early implementations where three different points of translation were highlighted (Stone 2015; Doytchinov *et al.* 2015). The contradicting proposed strategy in this work is to build the quality information exchange based on the already developed standards framework for MBD and manufacturing contexts. In another word, the measurement data models are developed as a continuation of the already developed models in STEP and not as a separate model that requires translation processes. Standards formats such as STEP are currently the natural output of the design stage and should lead to seamless data consumption by the downstream applications without any unnecessary post-processing of the designed data. Using the STEP framework will result in a quality data model that matches normal data flow within the product life cycle. This strategy supports overall manufacturing system interoperability and direct applicability of resulting data models.

4.5. Recap and critique of measurement standardisation

This chapter explored the research efforts done by the standard communities within the scope of this research. In section 4.1, the STEP (ISO 1994a) framework were described in detail as a means to unambiguously represent products and processes data. This description included the efforts done for modifying the STEP framework architecture to allow the reuse of the defined STEP-based information models and to attain extensibility and interoperability principles between various STEP modules. EXPRESS (ISO 1994d) and its graphical representation, EXPRESS-G, are described as being the modelling language and related graphical representation used by the STEP standards. This work is based on the STEP's modelling and implementation methods while considering the design and implementation of the proposed REIMS framework.

STEP is an extensive repository of data models that satisfies different perspective of a product within its lifecycle (Xu and Nee 2009; Kramer and Xu 2009). The author supports the opinion of Brecher *et al.* (2006) that a STEP-based measurement process model should be selected as the natural modelling strategy to ensure the interoperable integration of the measurement process with both design and machining data. STEP also is implementation independent that makes STEP adaptable for the legacy, current and future information technologies and requirements.

STEP developments towards satisfying the MBD and manufacturing requirements were addressed. STEP AP242 (ISO 2014a) data model enabled interoperability of CAD and PMI data among CAD systems (Lipman and Lubell 2015; Frechette *et al.* 2013), however, this exchange format has not yet been evaluated with respect to the requirements of the measurement applications (Fischer *et al.* 2015); which also applies for CAM applications. REIMS prototype implementation uses AP242 for evaluating this capability as described in Figure 7-1.

The author has identified that the STEP provides a limited representation of measurement data. STEP-NC part 16 (ISO 2004) misses the representation of measurement features and its representation of measurement operations is limited. On the other hand, STEP AP219 (ISO 2007b) represents measurement features but ignores any information regarding modelling of various measurement and analysis operations. REIMS aims to provide a framework that is able to extensively and explicitly represents both measurement features and operations based on the introduced concepts in ISO GPS standards. Table 4-7 clarifies how the proposed REIMS data model fits within the STEP standardised framework to fill the gaps presented in the current STEP-based measurement data models. Table 4-7 indicates that STEP could provide a framework to integrate measurement within the product lifecycle as it includes necessary

Table 4-7: STEP, QIF and REIMS product data and measurement data representations

	AP242	AP224	AP238	AP219	QIF/ DMIS	REIMS
Geometry	(✓)	✓	✓	✓	✓	✓
Topology	(✓)	✓	✓	✓	✓	✓
GD&Ts	(✓)	✓	✓	✓	✓	✓
Machining features	X	✓	(✓)	✓	X	✓
Machining operations	X	X	(✓)	✓	X	✓
Measurement features	X	X	X	✓	✓	✓
Measurement contact extraction operation	X	X	limited	X	✓	✓
Measurement non-contact extraction operation	X	X	X	X	X	✓
Measurement analysis operations	X	X	X	reporting only	✓	✓

Legend: ✓ supported X not supported

(✓) Latest definitions used in this research manufacturing perspectives within one platform such as MBD, manufacturing features and manufacturing process plans.

In section 4.2, the ISO GPS standardised series was introduced as being the only framework that considers the design specifications and thier verification requirements in relation to each other to remove any ambiguity and misinterpretation of design data. ISO GPS theoretical foundation should be the base of the development of measurement planning data models as it includes the feature and operation concepts that match the modern coordinate metrology process. The ISO GPS concepts were introduced such as geometric features, characteristics and conditions, operator and operations and total uncertainty concepts. These concepts are not yet adopted by current CAD systems. The author has identified that the ISO GPS concepts are formatted in a text-based manner for human understanding rather than for being used by the computerised applications. This work targets increasing the potential of these introduced concepts and their applicability within the digital manufacturing through encoding them into a computer interpretable formats. This enables the use and exchange of these concepts by computerised applications and their consumption by downstream activities (Ballu *et al.* 2015).

In addition, the author has argued the main strategy followed by the ISO GPS committees. The committees have based their philoshophy on the assumption that a complete specification operator to eliminate the specification uncertainty is achievable. This requires that the designer is fully aware and understands modern coordinate metrology tools and software, which may be unrealistic. The designer could only specify those features that are related directly to the functional requirements, but the designer is unable to specify the intermediate features and their related analysis operations that exist only following to the start of the measurement process. These types of features are not controlled or produced during the manufacturing processes to be specified by the designer. The author believes that the measurement process can be defined through the interaction with the design specifications and completed with the aid of metrology expertise and knowledge. The author's opinion agrees with the basic characteristic definition introduced in ISO 25378 (ISO 2011) as it does not include the definition of intermediate features.

Sections 4.3 and 4.4 introduced the DMIS and QIF standards as the currently applied measurement standards in industry. DMIS is an execution language that can achieves interoperability only between CMMs (Savio *et al.* 2014; Zhao *et al.* 2012). In addition, DMIS is not integrated into the STEP extensively developed framewrok (Brecher *et al.* 2006). Furthermore, Table 4-7 shows that DMIS lacks the manufacturing context as it does not have manufacturing features or operations defeinitions. QIF is considered as an interoperable implementation of DMIS; consequently, it suffers from the same shortcomings presented for the DMIS standard. To conclude, a STEP-based measurement application could be integrated seamlessly with upstream applications without any unnecessary data conversions or translations as is the case today with the DMIS and QIF standard.

The main gaps to be addressed following surveying the standard developments efforts are:

1. **Evaluating state of the art in MBD**, STEP AP 242, **against measurement application** requirements.
2. **STEP-NC part 16 and STEP AP 219 are limited** with respect to representing a complete and explicit definition of measurement plans.
3. **ISO GPS introduced concepts are not formatted in a computer interpretable format** which hinders their applicability and benefits for digital manufacturing environment especially for measurement computerised applications.
4. **Measurement analysis operations and intermediate features were neglected** in the currently defined measurement data models.
5. **Measurement data model should base on STEP standards** to ensure its interoperable integration with upstream activities and to consider manufacturing context in parallel to measurement context.

5. Theoretical framework of resource independent measurement specifications

This chapter presents the theoretical framework of this work that aims to push the boundaries of the ongoing research of measurement integration and interoperability. This chapter commences in section 5.1 by portraying the necessary requirements to which the defined conceptual framework should conform. Subsequently, the established theoretical framework to address the identified gaps and requirements is presented in section 5.2.

5.1. REIMS theoretical framework requirements

This section introduces the various requirements to be fulfilled by the proposed REIMS data model. These requirements are as follows:

5.1.1. Representation of necessary data within REIMS scope

The REIMS framework should represent the required information for defining a measurement process in an unambiguous manner. Measurement process definition identifies “what to measure” depending on the design specifications or manual user selection, even if done through computerised interfaces. In addition, measurement process definition is required to specify the manner and time of each measurement step. It should be emphasised that the “how to measure” question does not mean only to define extraction data, but also all the other decisions necessary for applying measurement data analysis and evaluation steps to match the modern coordinate metrology requirements.

Information such as geometry, topology, characteristics, datums and tolerance zones should be considered from the design phase. Moreover, REIMS needs to represent both measurement features and measurement operations that are defined during the measurement planning phase. The requirement to represent measurement features and operations is necessary to overcome the current STEP-based measurement standards’ limitations discussed in subsections 4.1.7 and 4.1.8. The limits of the represented data within the REIMS framework should be determined by functional analysis methods and exploration of available standards for specifications and measurement process. Functional requirements are tasks, actions or activities accomplished by the system being analysed. Functional analysis is carried using Icam DEFinition for Function Modelling (IDEF0) method within the STEP framework, where Icam is an acronym for Integrated Computer-Aided Manufacturing.

IDEF0 method depicts activity constraints rather than only showing the data flow between activities (Feldmann 2013); making IDEF0 different from other data flow diagram models such as block diagrams and flow charts. Activity constraints are the necessary inputs and controls to activate a specific functionality. Feldmann (2013) further argued that IDEF0 is the only method that could be used in early problem-definition stages, rather than only describing a well-defined process, which matches the proposed framework objective to define a new system. Another advantage of IDEF0 is that it can deal with many types of entities such as people, data and software.

5.1.2. Integration with other product lifecycle stages

REIMS should enable integration at the connecting data interfaces at both ends of the measurement process definition. Hence, the proposed framework should be able to integrate measurement process definitions with other product lifecycle contexts. Integration means the ability to exchange data from and to other CAx applications and not to be formulated as an isolated activity. In this work, integrating measurement data with CAD/CAM systems is a crucial requirement of the proposed framework.

The integration with CAD systems is necessary to allow direct consumption of design data such as geometry, topology and characteristics. Direct data consumption leads to the elimination of unnecessary data translation or recreation from the design stage within measurement applications. Furthermore, the integration with CAD systems should be bidirectional to provide the measurement information back to the design stage. Designers can use measurement data for early design evaluation and further development steps. On the other hand, the integration with CAM data results in two main outcomes:

1. The definition of in-process measurement could be integrated within machining planning.
2. The manufacturing process can benefit from measurement data being linked to manufacturing features and operations information. This allows the manufacturing control functionality of the measurement process, where measurement data is used as feedback from the production process.

It should be noted that the integration requirement with CAM systems should not prevent the formulation of an independent measurement specification for conformance checking or reverse engineering processes. In fact, the integration of REIMS applications on one side and resource-dependent programming and execution applications, on the other hand, is dependent on the used framework on programming and implementation stage. This integration should ideally be based on the STEP standard to fulfil the full integration and interoperability requirements, but unfortunately, this is not practical, as the controllers of measurement equipment do not support STEP-based frameworks. STEP-based measurement framework is not the only application that suffers from the lack of STEP-based controllers, as full integration of STEP-NC and QIF, for examples, is blocked in a similar manner when considering measurement data.

5.1.3. Enabling interoperable data exchange of measurement process definition

REIMS should ensure that the integration requirements, as discussed in subsection 5.2.2, are achieved in an interoperable manner. Ensuring interoperability is important as further system development can be carried out based on standard formats by any developer and is not restricted to the system inventors (Nassehi 2007). It should be stressed that integration and interoperability requirements are two distinct needs. For instance, Panetto and Molina (2008) differentiated integration from interoperability as integration involves functional dependencies between various systems, while interoperability does not require this condition. According to their understanding, integrated systems must be interoperable while interoperable systems need not be integrated. Interoperability leads to compatible systems that can exchange and use data without any intermediate steps as they may depend on the same data models. Savio *et al.* (2014) and Savio (2012) concluded that ensuring interoperability of measurement systems positively affects manufacturing through potential cost-savings.

This research utilises the STEP modelling tools and methods described in 4.1 to enable the interoperability and integration requirements of REIMS with CAD/CAM systems. By default, STEP, being a standardised data exchange mechanism, enforces the interoperability requirement (Zhao *et al.* 2011a). STEP AP242 files for exchanging data are selected to represent CAD data in the proposed framework. AP242 is the only standard data format, which can represent GD&T information and is the only standard MBD that exists today. If necessary, the integration of REIMS with manufacturing and CAM data represented within the STEP-NC framework is established by the relationships between the definitions of both measurement features and manufacturing features. The proposed REIMS framework deploys STEP-based ASCII text files, ISO 10303-21 (ISO 1994c) as the data exchange mechanisms. It should be emphasised here that an EXPRESS model is implementation independent; thus, any other necessary implementation methods for different applications can be exported based on the proposed EXPRESS model.

5.1.4. Compliance with standardised definitions and practice

An indispensable requirement of REIMS is to depend on standardised data models for enabling both integration and interoperability. Standardised solutions are more powerful than the proprietary ones as they have a wider scope of application and development (Savio *et al.* 2014). By definitions, open standards facilitate interoperable data exchange between different systems (Zhao *et al.* 2011a); that is the primary goal of REIMS.

From another perspective, the proposed framework should comply with various standard symbols, definitions and principles to be able to represent semantics as well as syntax. Within this work, different standards require consideration while representing data related to design, manufacturing and measurement. For example, the data model of REIMS should be able to carry data that is used to represent design specification and is based on AMSE Y14.5 or ISO 1101 standards. The proposed data model also should be able to contain measurement data and rules based on best practice guides and standards where exist.

5.1.5. Universality of the framework for different measurement purposes

REIMS should allow the definition of measurement specification for satisfying various measurement scenarios. Conformance checking, for example, requires both measured and nominal product data, which is not the case for reverse engineering requirements that require only the measured data without nominal definitions. Constructing a single framework that can serve different measurement perspectives and scenarios is an essential prerequisite of REIMS to be universally applied in various industrial applications. In addition, being universal means providing the possibility of defining a measurement specification related or independent of the manufacturing process information.

5.1.6. Object oriented implementation

REIMS is required to follow the object-oriented paradigm for data model design and representation. The proposed framework endeavours to produce prototype software implementations, which makes object orientation philosophy suitable for this intended objective. Object-oriented programming models the real world in the form of objects rather that actions that have its properties expressed as the objects' attributes. An object is a form of data structure that encapsulate the object attributes and the function necessary to operate on these attributes in a single defined unit called a class.

Object oriented programming has some efficient characteristics such as encapsulation, data abstraction, classes, information hiding, inheritance and polymorphism (Lafore 2002). C++ is most widely used and accepted as a low level and object oriented programming language. C++ is selected for REIMS as its core implementation-programming tool to produce the final software implementation prototype.

5.2. REIMS theoretical framework

A central concept of this research is that formulating and exporting a standard definition of the measurement process that is independent of any programming or execution methods, presented as the REIMS file in Figure 5-1, is an enabler for the interoperable exchange of measurement plans. This measurement process definition should also completely and explicitly identify not only measurement extraction information, but also analysis operations needed to process the extracted data; this is to guarantee a comparable measurement results that are produced from different geographically distributed measurement locations and by using various measurement equipment as demonstrated by Figure 5-1. The comparable measurement results, obtained through the exchange of a clear and explicit definition of the measurement process, ensure the consistency of the gained knowledge about both products and processes and hence reduces uncertainty expected in following decisions. The proposed framework is based on a standardised neutral format that is common between different CAx stations. Standardised neutral data formats eliminate unnecessary translations or post processing steps during data exchanging.

This research introduces a modified paradigm for measurement system analysis to realise the benefits of the proposed data model as a tool for removing interoperability barriers within the measurement system. Figure 5-2 illustrates the traditional measurement system stages and the currently applied standards for transferring measurement data through the overall measurement system. Likewise, Figure 5-2 identifies that the measurement planning stage is defined in a resource-dependent manner as it implicitly contains the programming activity, which, in turn, is tightly coupled with measurement equipment selected *a priori*.

Figure 5-3 shows the proposed framework for the measurement system through explicitly separating the measurement planning stage into two distinct stages. These

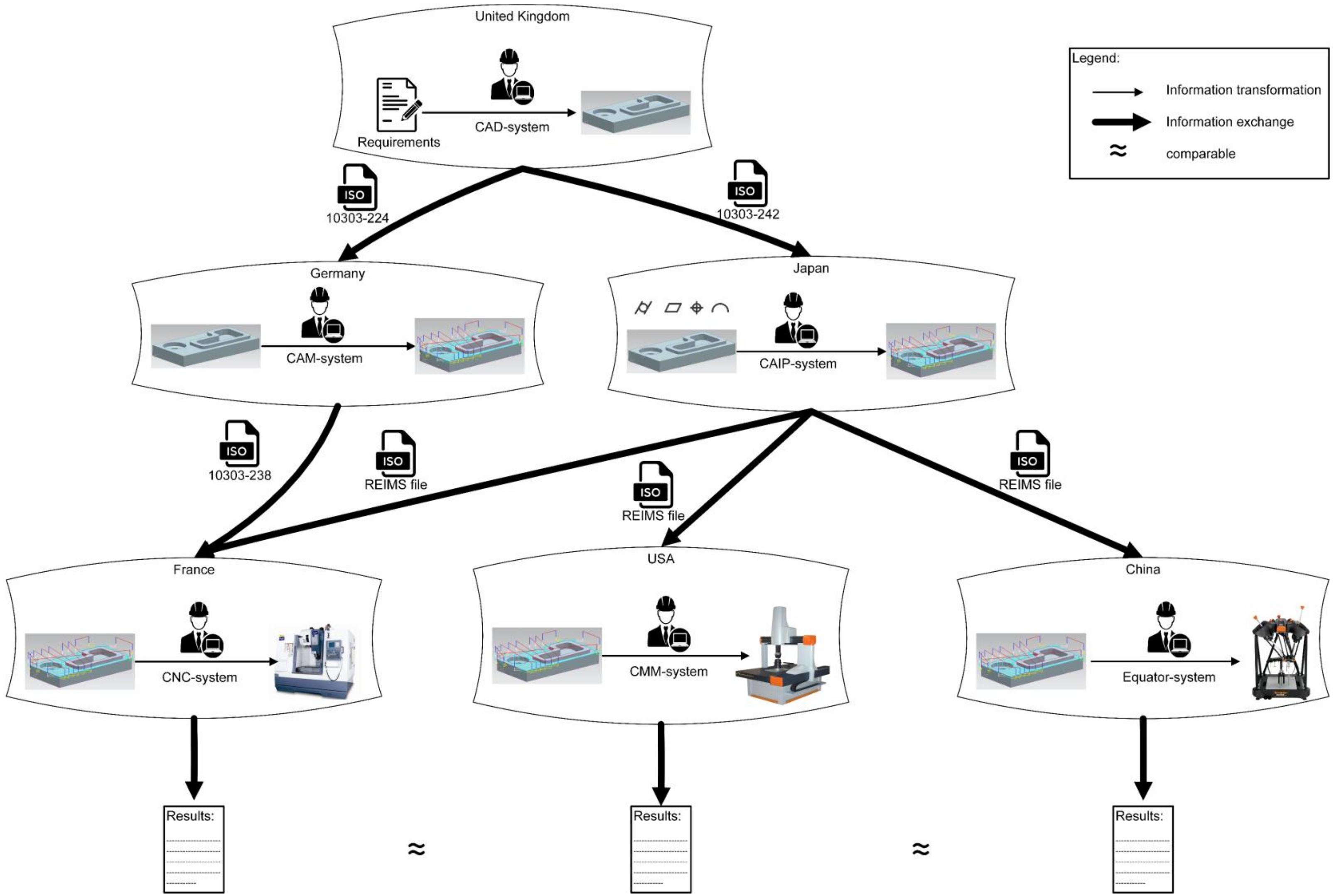


Figure 5-1: Interoperable exchange of measurement process definition

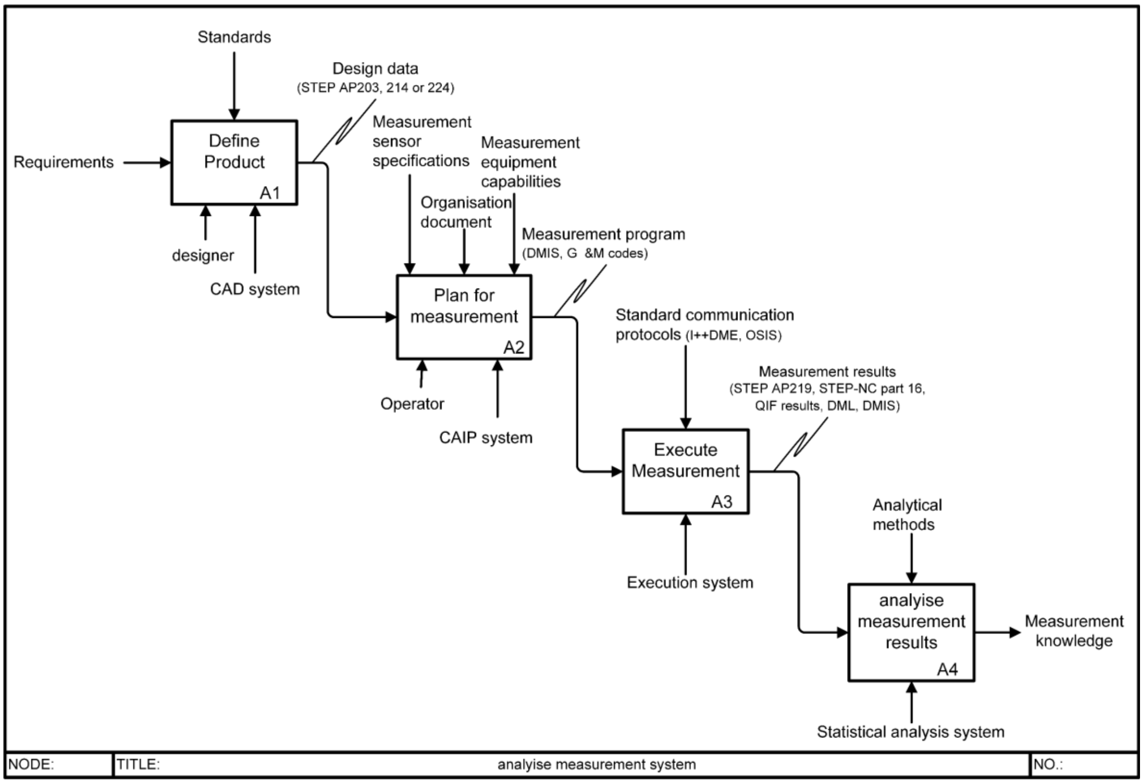


Figure 5-2: Traditional metrology system stages and standards

steps are measurement process definition and measurement programming stages. The goal of the modified framework is to enable the formulation of a standardised data exchange model that can hold necessary resource-independent data for defining a measurement process. The proposed model is entitled “resource-independent measurement specifications (REIMS)”; as mentioned in section 2.1. REIMS aims to remove the interoperability barrier shown as a dashed line in Figure 5-3.

The REIMS framework is required to exclude the representation of the data related to various measurement resources during the definition of the measurement process and to replace proprietary data formats used within CAIP systems. In other words, the proposed framework will define a model for representing a resource-independent measurement information such as measurement features and operations; this should enhance the flexibility of the measurement scheduling and enable the realisation of the interoperability requirements. Vichare *et al.* (2009) and Nassehi (2007) indicated that the STEP-NC philosophy is to represent machining operations and cutting tools data; REIMS extends the same philosophy to the measurement domain.

The REIMS system explicitly and unambiguously defines ***what is to be measured*** and ***how it is to be evaluated***. However, decisions regarding how to measure or extract

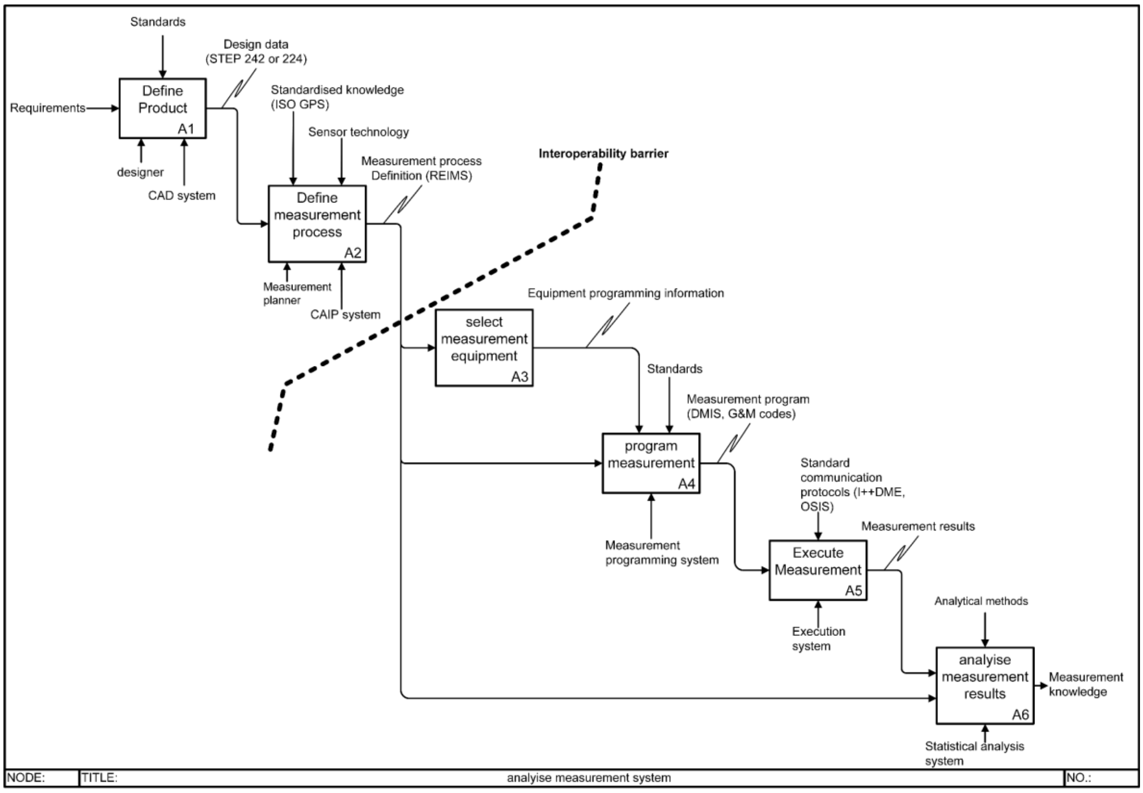


Figure 5-3: Modified metrology system for enabling interoperability of measurement

can only be specified in a technology-based manner rather than in a resource-dependent manner. To clarify, REIMS focuses on the product and process data rather than resources data, but it will provide some requirements for selecting the proper measurement resources based on their capability. The term "REIMS" is intended to replace the term "measurement-planning" to reflect the idea that it excludes the programming activity from its scope. Figure 5-4 shows how the measurement planning macro and micro activities can be reclassified based on the dependence on the measurement resources information; the resource-independent elements are included within the REIMS data model.

The REMIS system is based on feature technology as an integration enabler. Feature technology is the principle upon which the integration between different CAx applications such as CAD/CAM has been realised. It should be noted that different applications use different feature definitions. For example, Zhao *et al.* (2011a) clarified that design features are not the same as manufacturing features. Design features are used in CAD systems during the product conceptualisation phase by being added or removed to alter the final shape of the product boundary. Manufacturing features are utilised in CAM systems to identify the volumes to be removed from an initially defined

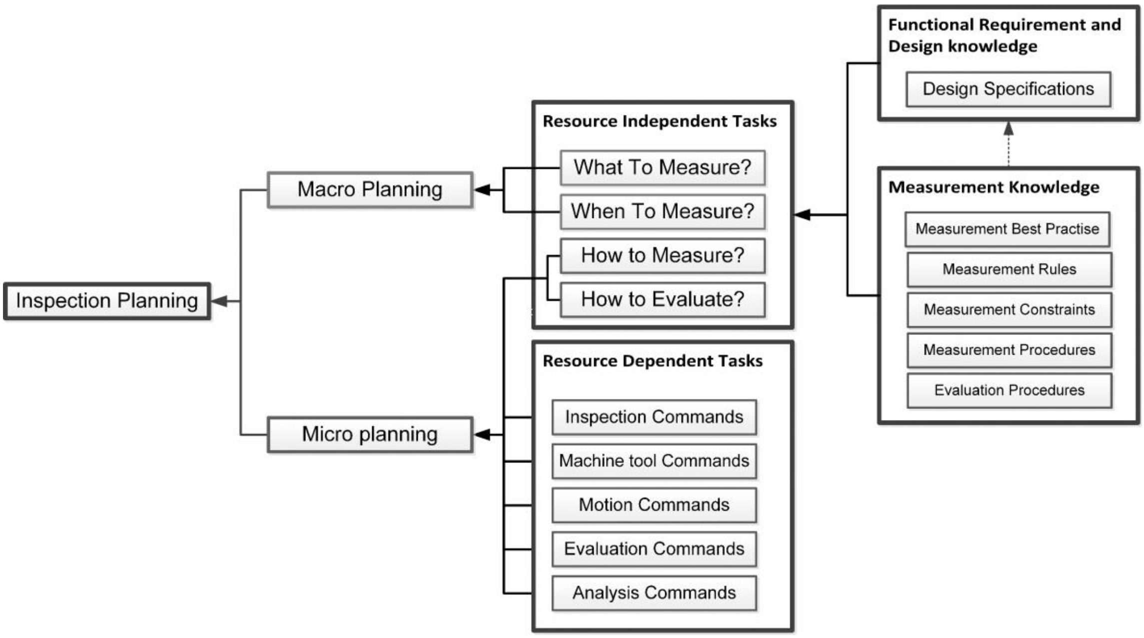


Figure 5-4: Resource dependency of measurement planning activities

raw material through a set of machining operations to reach the final product. In general, the designed product consists of a collection of 3D features. During the design phase, the nominal form, size, location and orientation of those features are characterised both geometrically and dimensionally.

The example shown in Figure 5-5 clarifies that the design specifications control only 2D geometric entities, although being specified from the design perspective to control the variation of the 3D features' parameters. Consequently, only the product final boundary is measured as being represented by various 2D geometric entities. These measured entity features are distinct from manufacturing or design features (Zhao *et al.* 2011a). For instance, a single manufacturing feature may be associated with various measurement features based on control specifications. Furthermore, measurement features can be related to other entities related to other manufacturing features.

It should be emphasised that measurement items cannot be represented independently of the other feature types that convey related designed function or manufacturing operations (Brecher *et al.* 2006). For example, the flatness tolerance, in Figure 5-5, controls the planar face feature, which is directly measurable as it is an integral part of the product boundary. On the other hand, the position tolerances control the axis of the hole feature and the central plane of the slot feature. Both axis and central plane are constructed using other directly measurable integral features, as they are not part of the workpiece boundary. The presented variation in features' dimensionality should be considered in the REIMS data model.

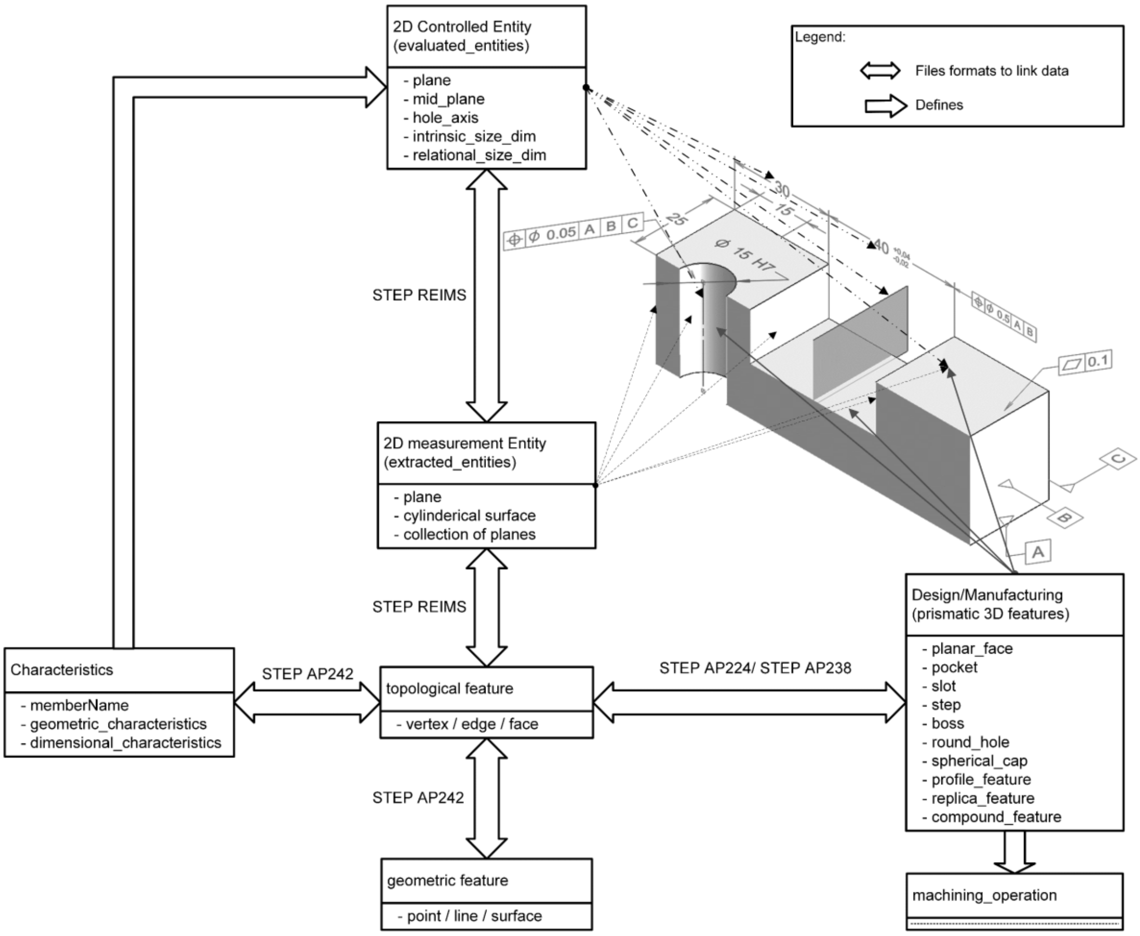


Figure 5-5: Illustrative example for representing different views of features

Currently, necessary links between different features dimensionality are distributed in various STEP parts. For instance, in Figure 5-5, the positional tolerance is applied to the central plane of a slot feature. This central plane is derived from the two integral slot sides. The relation between the design specification and the part geometric entities can be embedded in a STEP AP242 file that is exported from CAD systems. Conversely, the relation between the same geometric entities and its parent-manufacturing feature is only defined in STEP AP224, which is intended to be consumed by CAM systems. The REIMS system perspective is that both types of relations should be available within a single framework to enable the definition of the measurement features related to specific design characteristic and at the same time relate the measurement results to the machining operations related to the parent manufacturing features.

Finally, REIMS is also constructed in an operation-based manner that is derived from the theoretical operations concepts defined in ISO GPS standards as discussed in subsection 4.2.4. As a result, REIMS can be directly linked to the design specifications through the precise definition of the controlled and measured 2D entities and their related inspection operations based on the ISO GPS concepts. Figure 5-6 presents a UML conceptual model to clarify the measurement process definition in REIMS as being formulated in an operation-based manner that is related to defined measurement features; Figure 5-6 also clarifies the relation between feature dimensionalities in REIMS.

In Figure 5-6, a `solid_model` is composed of `characterised_3d_feature`(s) that are related to specific `machining_features` and operations as

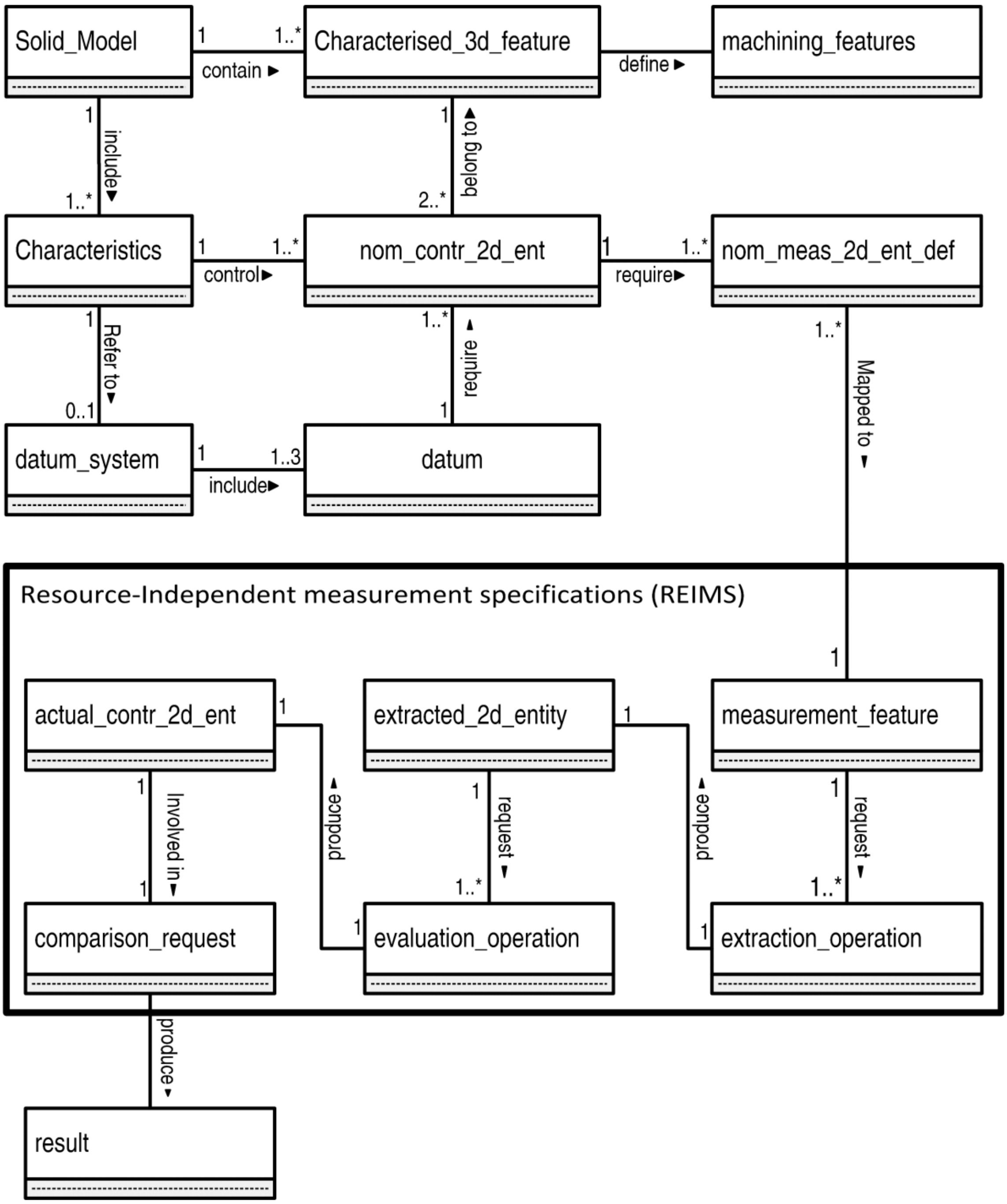


Figure 5-6: REIMS conceptual framework and inter-feature relations

defined in CAM systems. The solid model definitions include some characteristics that are specified by the designer to control 2D geometric entities, nom_contr_2d_ent. These characteristics also may include datum_system(s) that define datum(s), which, in turn, refer to 2D geometric entities. The referenced nom_contr_2d_ent(s) by the specifications and datums are classified as being integral or derived entities; the derived entities then are processed to get their deriving-integral geometric entities. Hence, the integral 2D geometric entities required to be measured by measurement process are determined, nom_meas_2d_ent_def. The measurement plan can then be constructed in an operation-based manner given that each integral 2D entity requires an extraction_operation definition followed by evaluation_operation(s) to obtain measurement features. Finally, a comparison_request is triggered to compare the evaluated data with respect to the nominal data and the specified characteristics.

6. Realisation of the REIMS data model

In this chapter, the REIMS data model is specified to accommodate the stated requirements and functionalities described in chapter 5. This chapter starts by describing the top-level data model entity representing the measurement specification in section 6.1. Section 6.2 follows by exploring the representation of measurement features in the REIMS data model. The representation of measurement operations required for obtaining measurement features is introduced in section 6.3. Finally, section 6.4 explores the representation of geometric and dimensional characteristics in addition to datums and tolerance zones in the data model.

6.1. REIMS data model top-level entity and its integration within STEP framework

A measurement plan may be formulated independently or as a part of a machining process plan and REIMS should be able to represent both scenarios. The REIMS data model design is therefore based on the existing framework within STEP AP238 ISO (2006b), as it provides a data structure suitable for integrating measurement specifications with machining information. In addition, the AP238 data structure offers flexibility that allows REIMS, not only, to describe measurement process definition as a part of machining process plan, but also, to define an independent measurement process plans. Independent measurement specifications are required in cases such as in-situ measurement applications where the workpiece is removed from the machine tool and measured in different locations which may be near the machine tool or in an environmentally controlled measurement laboratory (Zhao *et al.* 2011a).

The STEP AP238 framework includes the definition of `project`, `workplan`, `executable` and `workingstep` as entities to capture the logic of a machining process plan. The top-level `measurement_workingstep` entity, as a new type of workingstep, is thus introduced into REIMS to define the measurement process. Defining `measurement_workingstep` as a subtype of executable makes it possible to integrate in-process measurement operations, performed on machine tools, within the machining process to build a single integrated process plan for machining and measurement. An independent measurement process definition can also be constructed using this design by specifying a sequence of `measurement_workingstep` entities. Figure 6-1 illustrates the `measurement_workingstep` entity as a subtype in the inheritance tree of the `executable` entity as defined in the STEP AP238.

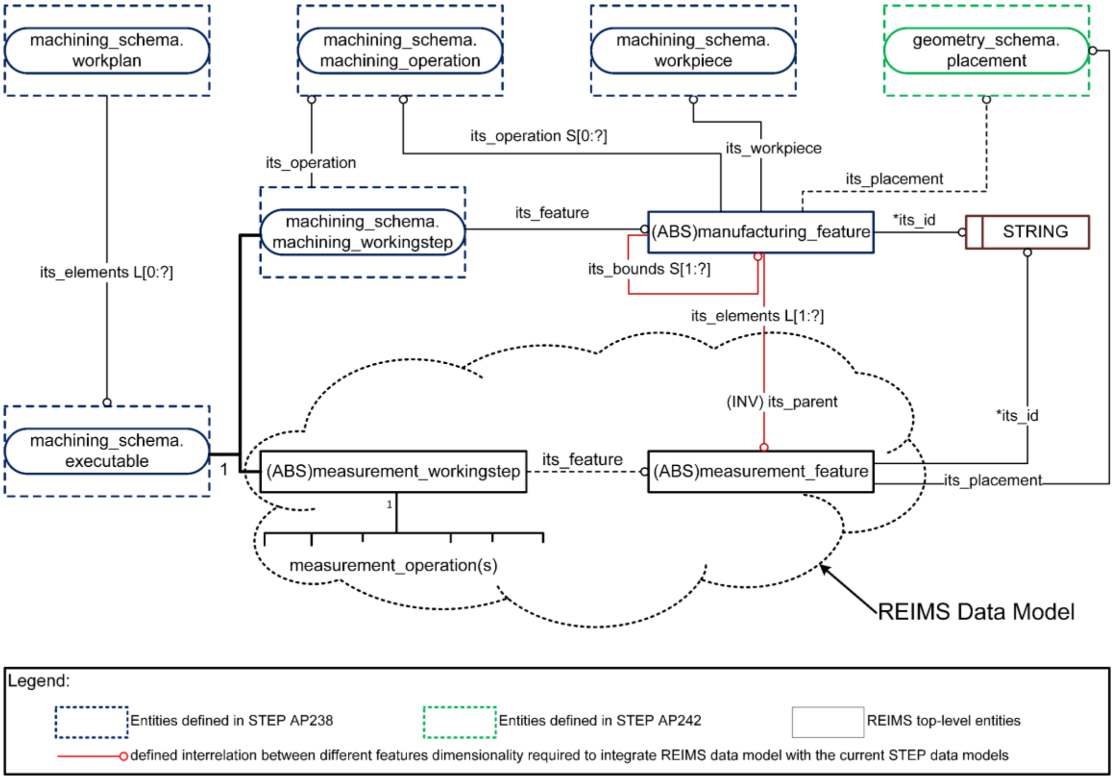


Figure 6-1: The REIMS data model and links with STEP AP238

The author believes that, where possible, referencing entities that are already defined in other APs within the REIMS data model is a better strategy than defining new entities that may later require harmonisation and additional effort for integration within other frameworks. It should be noted that the REIMS design requires a modification to the relations defined in the STEP AP238 between `project`, `workplan` or `executable` entities and design data to make them optional to allow the representation of the reverse engineering case scenario.

Figure 6-1 also shows the dimensionalities of features and their interrelationships for enabling the integration of the REIMS data definitions with other STEP data models as was previously discussed in section 5.2 and Figure 5-6. As shown in the figure, the `manufacturing_feature` entity is related to `measurement_feature` child entities through the `its_elements` attribute. This link is crucial for realising measurement as an enabler for controlling manufacturing processes. This is achieved by directly connecting the measurement results to the `machining_operation` that creates a `manufacturing_feature` as shown in Figure 6-2. Consequently the measurement knowledge gained can be directly used to update the parameters of machining

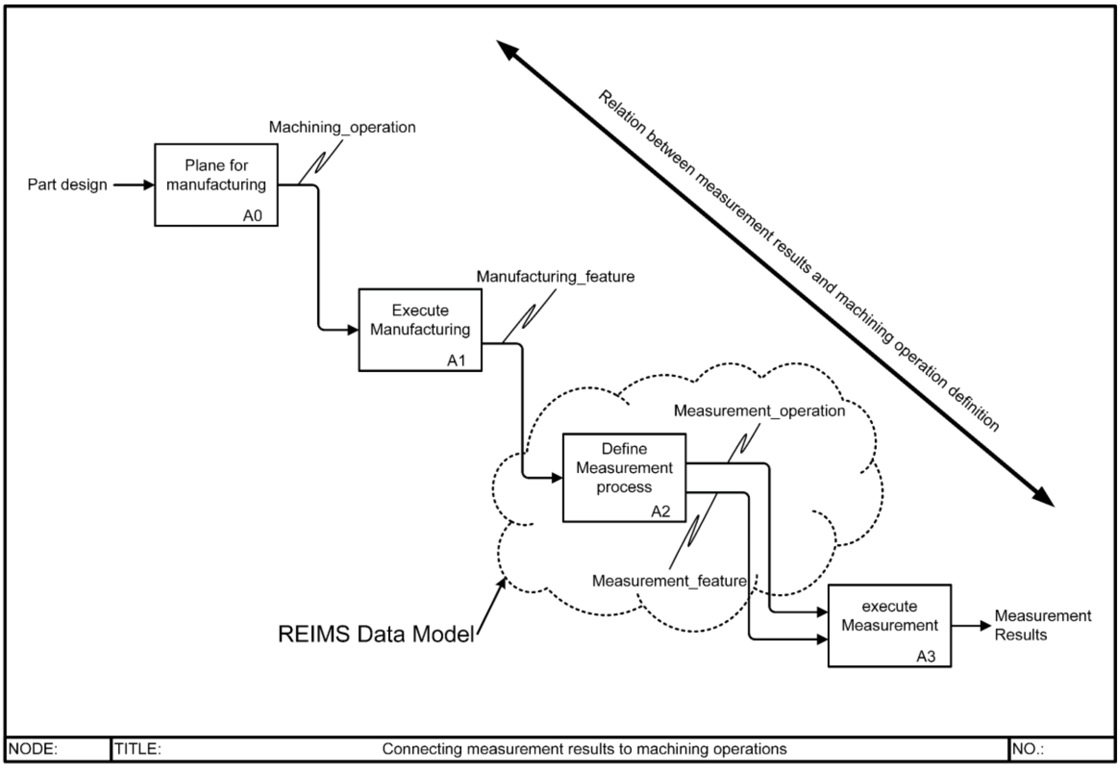


Figure 6-2: Measurement results and machining operations links in REIMS

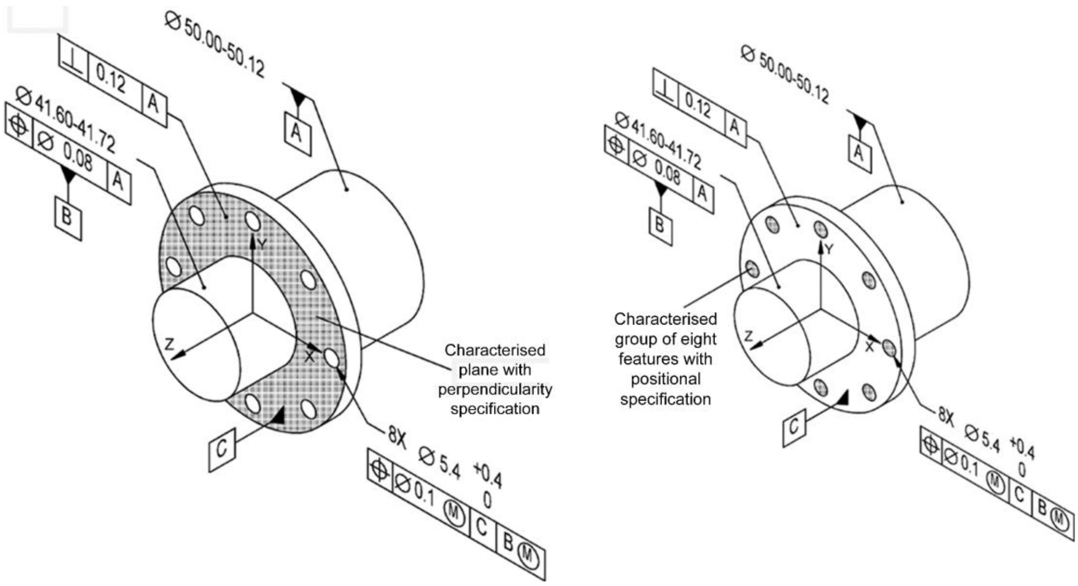
operations allowing adaptive process plans that are necessary for modern manufacturing trends.

It should be noted, however, that this mainly concerns pre-finishing or finishing machining operations that relate to the final product boundary and hence require checking by measurement processes; roughing operations other than ones that immediately precede finishing operation are not typically linked with measurement operations. In addition, by considering measurement as a control enabler, the REIMS model proposes a modification for the 2.5D manufacturing feature definition. This modification requires the 3D feature to reference its bounding 3D features as shown in Figure 6-1. This is necessary as a machining operation of the bounding feature may affect the size parameters of the bounded feature. Consequently, any measurement error in the evaluated size parameter may require updating of the parameters of machining operations related to one of the bounding features rather than the machining operations parameters of the bounded feature itself.

Based on these interrelations, simple rules can be derived. For example, if measurement features that are linked to a dimensional characteristic both belong to the same parent manufacturing feature, the dimensional characteristic would be an intrinsic characteristic, i.e. a size parameter of a feature of size. On the other hand, if each of the dimensionally characterised measurement features refers to different parent machining feature then the characteristic is a relational one. The latter could be applied to locate a 3D feature with respect to another 3D feature, or it could result from the independent positioning of different 3D features as observed in the case of wall thickness. These inferred rules support the semantics derived from the REIMS data model introduced in this research.

6.2. Measurement features

Measurement features can represent a single geometric entity or a group of single geometric entities collected and controlled by a single design specification. Figure 6-3 shows an example part from the ASME Y14.41, (ASME 2012), including a perpendicularity specification of 0.12 mm tolerance zone that is applied to a single geometric entity, shown as the shaded plane in Figure 6-3 (a). This part also includes a positional specification of 0.1mm diametrical tolerance zone that is applied to a group of eight hole features, shaded in Figure 6-3 (b). Applying a specification to a group of features practically means imposing positional or/and orientation constraints on tolerance zones of the single features included within the group. Figure 6-4 shows the representation of the measurement feature supertype-entity and its inheritance tree. In this figure, `dmf_single` and `dmf_group` are subtypes of the `measurement_feature` abstract entity. The two entities are defined to represent the single feature and group of



(a) (b)

Figure 6-3: Single feature (a) and group of features (b) as toleranced entities; Modified from ASME (2012)

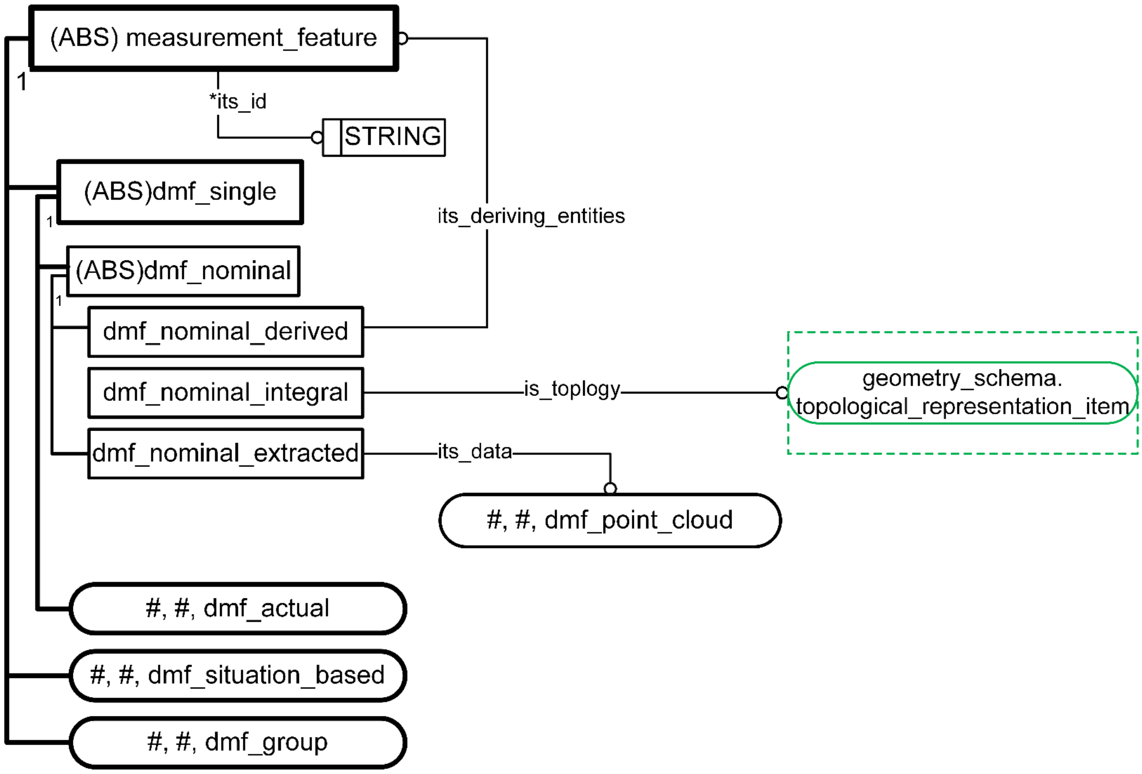


Figure 6-4: REIMS measurement feature

features respectively; these features can be controlled by design specification or be used within measurement environment.

A single measurement feature can be investigated through three mutually exclusive classifications:

1. Based on the representation of the feature's geometric shape

A geometric feature can be a point, a curve or a surface. Figure 6-5 illustrates these three basic geometric representations for features. These geometries are represented as supertype abstract entities in STEP AP242 (ISO 2014a). All other geometric representations are defined as subtypes of these entities. In general, the geometric information can be derived from overlaying topological information represented in a design file such as vertex, edge or face entities. These topological entities are referenced within the REIMS data model from `geometry_schema` represented in STEP AP 242 as shown in Figure 6-4.

2. Nominal definition versus actual measurement

A measurement feature could be either nominally defined or actually measured. The nominal entities exist in the specification environment where they are directly linked

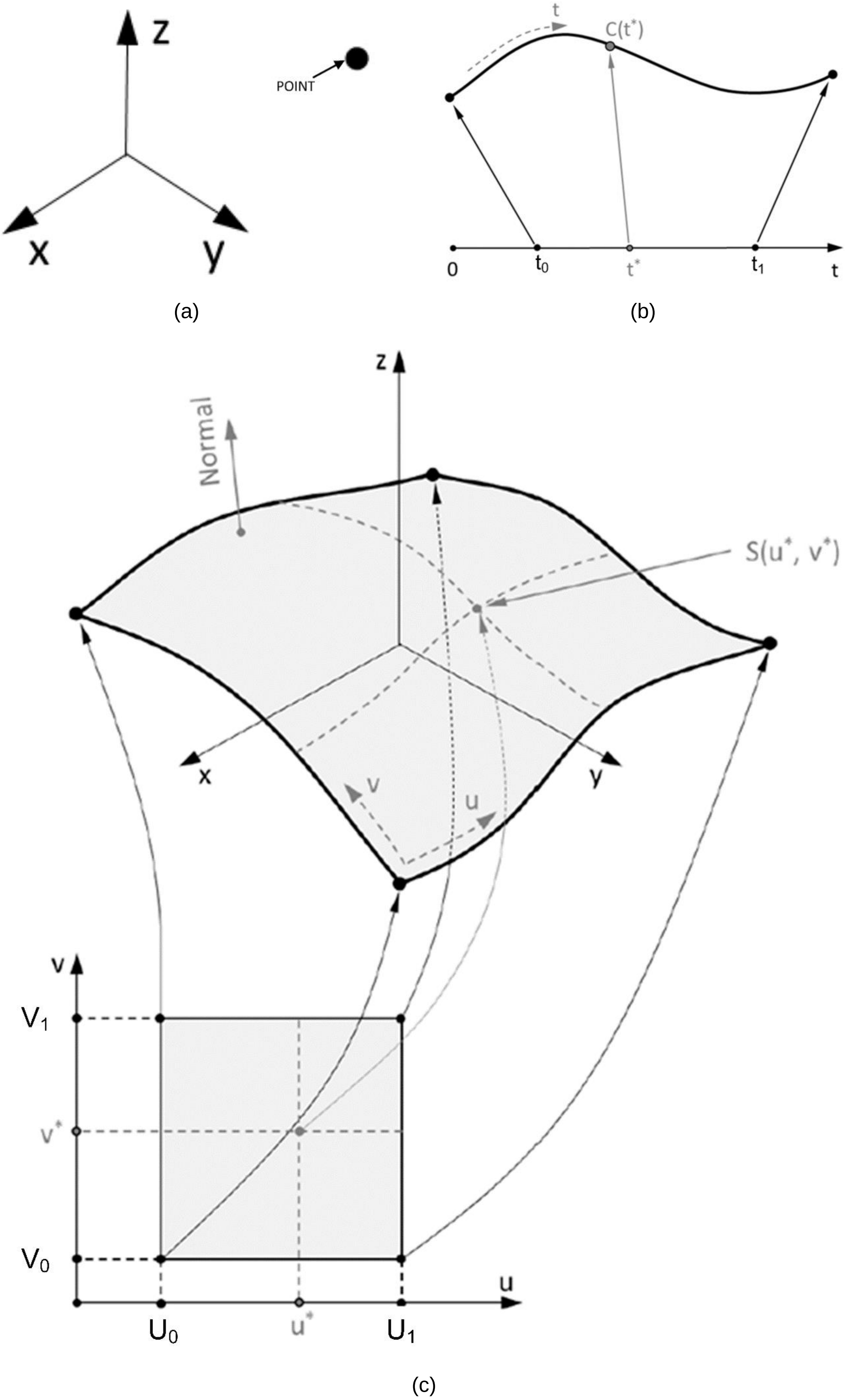
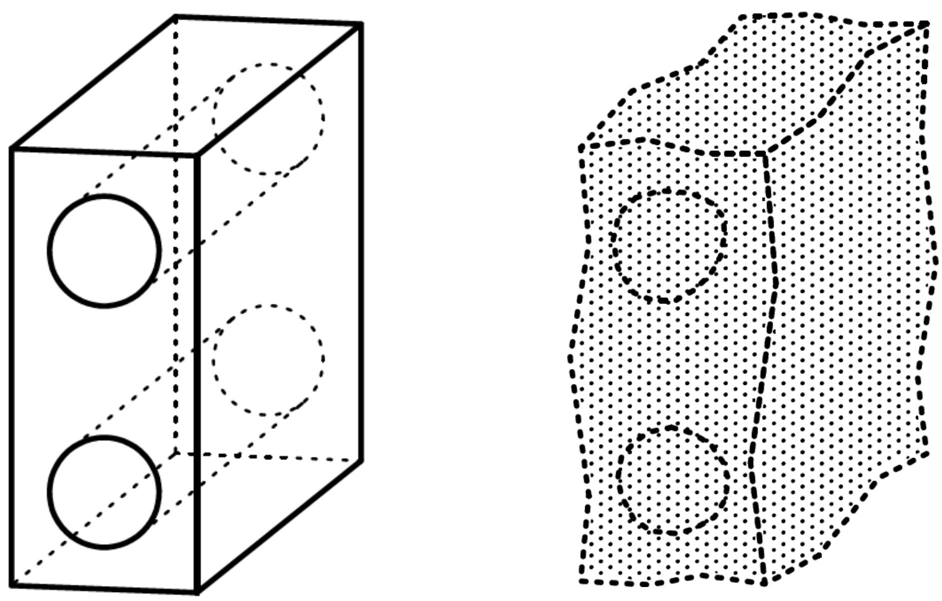


Figure 6-5: Various geometric shapes of a single measurement feature (a) point, (b) curve and (c) surface; Modified from ANSI (2014b)

to the specified characteristics. The nominal definitions are the as-designed data of geometric representation entities. On the other hand, the actual measured entities only exist in verification environment as they are resulting from the application of measurement technologies on manufactured surfaces. The actual feature also represents the processed data that is manipulated via measurement software tools and algorithms. Figure 6-6 shows an example part in the nominal and actual environments as introduced in ISO 22432 (ISO 2011i). In Figure 6-4, `dmf_nominal` and `dmf_actual` entities are introduced to represent explicitly the different environments that a feature can be dealt with by measurement process.

3. Integral versus derived measurement characteristics

Integral elements are directly measurable while derived elements require a relation to other integral elements and defined construction operations that work on the extracted integral elements. Derived elements are the situation features defined in ISO 14660 and 17453-3 (ISO 2000, 2014b), to specify position and orientation information of its integral parent elements included in a feature of size. Figure 6-7 shows a visual example of integral deriving entities and their related derived elements. REIMS represents this nature of a controlled feature by introducing the `dmf_nominal_integral` and `dmf_nominal_derived` as shown in Figure 6-4. In this figure, the relationship between a derived element and its parent entities is explicitly represented via the



(a) (b)

Figure 6-6: nominal and actual models as represented in ISO (2011i)

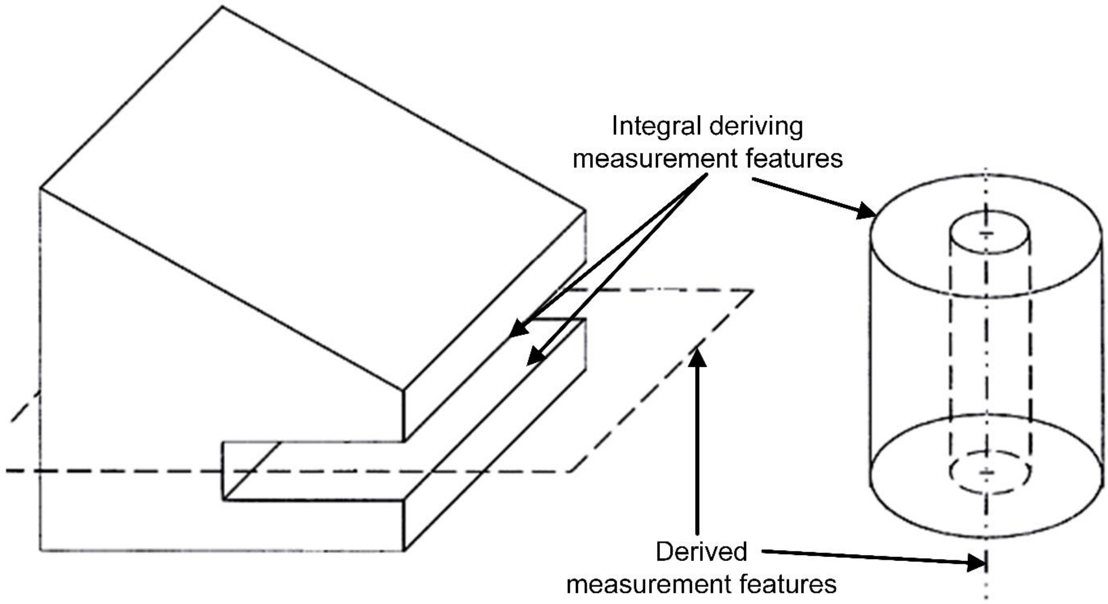


Figure 6-7: Integral and derived measurement feature; Modified from ISO (1997)

`its_deriving_entities` attribute. It should be noted that only integral measurement features have underlying topological representations and hence a related geometrical representation in the design exchange file. A derived feature does not have a topological representation in CAD models, but its geometric data can be derived given its parent integral element(s) and the definition of its construction operations. Nominal environment not only includes the integral and derived features but can also include point data that is planned to be measured or extracted from a specific integral feature. The `dmf_nominal_extracted` entity, as shown in Figure 6-4, is defined as a subtype of the `dmf_nominal` entity to hold points data planned for a measurement extraction. The `dmf_nominal_extracted` entity is referenced as an attribute of `extraction_planned_data`, discussed in section 6.3.1 and shown in Figure 6-17.

Figure 6-8 shows the representation of actual features that only exist after the start of the measurement process. Data collection and data analysis are two distinctive phases that need to be unambiguously defined and planned ahead of the execution of measurement tasks to reduce the overall process uncertainty. Actual features are those features collected from real part surfaces or those features that result from a specific evaluation operation such as filtration or fitting analysis step as discussed in features and operations concepts in sections 4.2.2 and 4.2.4. The `dmf_extracted`, `dmf_segmented`, `dmf_filtered` and `dmf_constructed` entities are introduced as

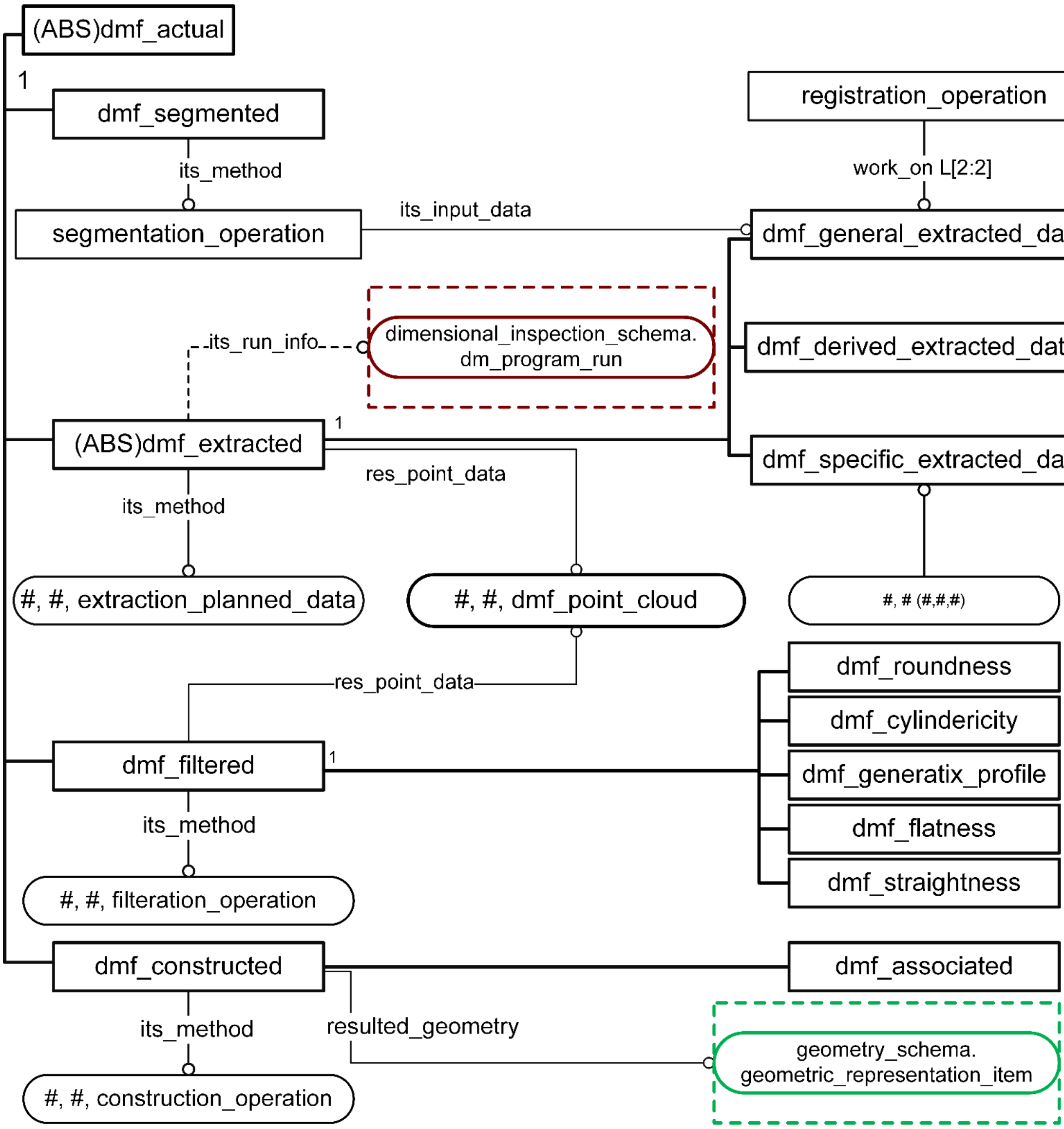


Figure 6-8: REIMS actual measurement features

subtypes of the `dmf_actual` abstract entity to represent various actual measurement features.

The `dmf_extracted` entity is a supertype entity defined to represent the point cloud resulting from a measurement extraction operation. The counterpart of the `dmf_extracted` entity in the specification environment is the `dmf_nominal_extracted` entity. Figure 6-9 shows an example of an actually extracted measurement feature. The `dmf_extracted` entity has two attributes for relating it to the extraction planned data, as represented in REIMS, and program run information, as defined in STEP AP219 (ISO 2007b). In addition, the `dmf_extracted` entity references a `dmf_point_cloud` entity as a third attribute to hold the point data

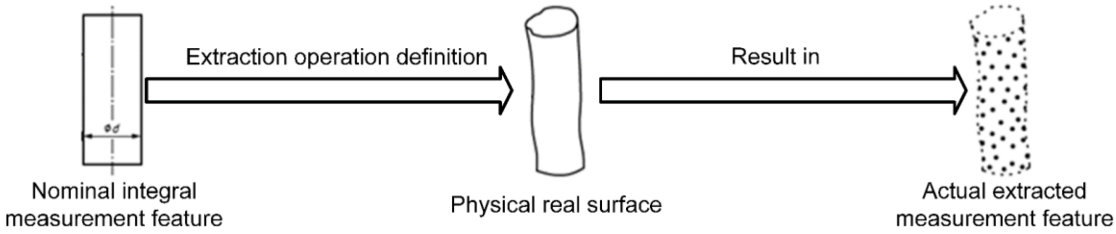


Figure 6-9: Actual extracted features and their relation to nominal integral features

forming the representation of its subtype entities. The dmf_extracted entity has three different subtypes as shown in Figure 6-8. The dmf_general_extracted_data entity represents point data that is not directly related to a specific measurement geometric feature; optical non-contact scanning technology is a typical example for generating such feature data. The dmf_general_extracted_data entity may require further processing for defining point data related to specific measurement feature using a segmentation operation resulting in point data subset that is represented by the dmf_segmented entity. On the other hand, the dmf_specific_extracted_data entity is defining the point data related to a specific measurement feature such as the case in contact based measurement operations. In addition, the dmf_derived_extracted_data entity is defined to represent constructed point data on a controlled derived feature using the extracted point data of its deriving features; this is commonly used during the evaluation of position or orientation characteristics.

The dmf_point_cloud entity is a subtype of the measurement_feature that is referenced by both dmf_nominal_extracted, dmf_extracted and dmf_filtered measurement features. The dmf_point_cloud entity is used to reflect the nature of data gained and processed within coordinate metrology systems. This entity represents point cloud data that is a list of coordinates. Figure 6-10 shows the dmf_point_cloud entity representation. Other information may be required to complete the definition of point cloud such as normal vectors attached to point data if provided by the measurement system. Also, a boolean attribute is allocated to indicate whether the included point data has been compensated or not, i.e. raw data. Compensation information is required if the is_rawdata attribute evaluates to true. Finally, the measurement points can be specified as being as an ordered or unordered set of data points.

Figure 6-8 shows the dmf_filtered and dmf_constructed actual measurement features that result from processing extracted data by filtration and

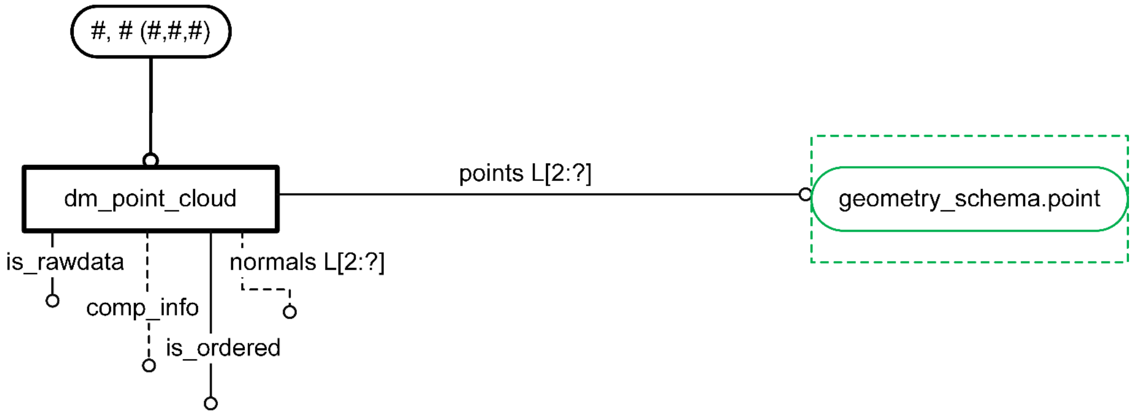


Figure 6-10: REIMS point cloud

construction operations respectively. The `dmf_filtered` feature is a processed `dmf_extracted` feature to remove unnecessary signals from the feature according to evaluation objective. The `dmf_filtered` feature is used to obtain roughness or form profiles that are used in the evaluation of roughness or form characteristics. A `dmf_filtered` entity references the filtration operation and the resulted point cloud from this operation as its attributes. There are different cases that may require a `dmf_constructed` entity, and therefore there are different subtypes of construction operation that will be discussed in subsection 6.3.4. Figure 4-17 is an example that shows how the filtration and association operation are used to get filtered and associated features for evaluating deviation from the nominal definition; the `dmf_associated` feature is a subtype of `dmf_constructed` feature that represents fitted features to extracted or filtered data.

In Figure 6-4, the `dmf_group` represent the measurement feature that is defined as a group of `dmf_single` entities as illustrated in Figure 6-3. The feature group concept is necessary to be represented as in measurement there are scenarios where a group of features is processed as a single unit. For example, a group of entities can form a single datum, or it can be controlled with a single design specification; both cases are shown in Figure 6-11. The `dmf_group` abstract supertype entity is defined to represent a group of measurement features as shown in Figure 6-12. Different subtypes of `dmf_group` are defined to reflect various cases in which a group of features is used within specification or measurement activities. For example, The group of features forms a pattern if the included single elements in the `dmf_group` entity are of the same base feature type as is the case illustrated in Figure 6-11. A pattern can be of a rectangular, circular or any other general form. On the other hand, if the single elements forming the

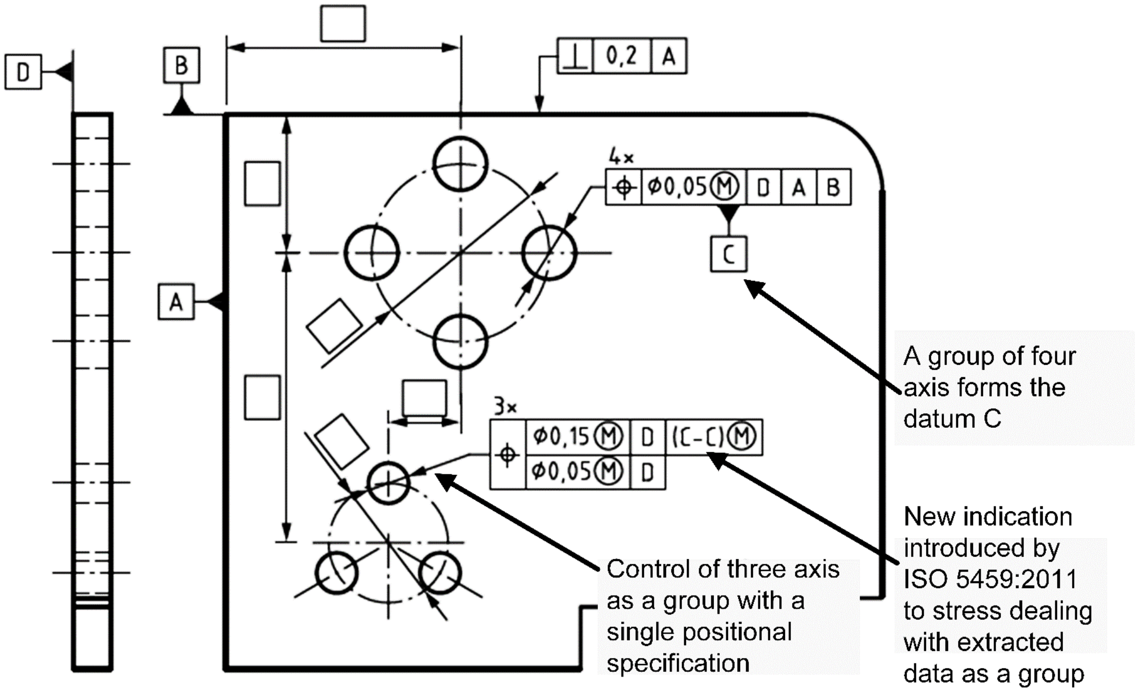


Figure 6-11: Feature group example; Modified from ISO (2011a)

dmf_group feature are of different types, the group is then called a dmf_collection, which is related to ISO GPS collection operation to relate different features together for a specific purpose. Figure 6-13 shows one example that requires the application of dmf_collection entity where the two sides of the machined slot are considered together as a collection that is used to derive a median situation plane.

Two subtypes of the dmf_collection feature are used to represent two specific cases described in the standard documents as follows:

1. The first subtype is the dmf_compound entity that is defined to represent a collection of measurement entities that share the same location and orientation data in 3D space. An example of a dmf_compound feature is a group of cylinders or cones of different diameters that share the same axis and are considered together from the functional and hence the measurement perspective. Another example is when a common datum is defined by continues features that result from the same machining operations and then interrupted by other features. These continuous features are defined in ASME Y14.5, ASME (2009) and are represented in the REIMS data model by the dmf_continuous entity which is a subtype of the dmf_compound entity. Figure 6-14 shows an example of the dmf_continuous entity where the top surface of the two bosses is specified as a continuous feature.

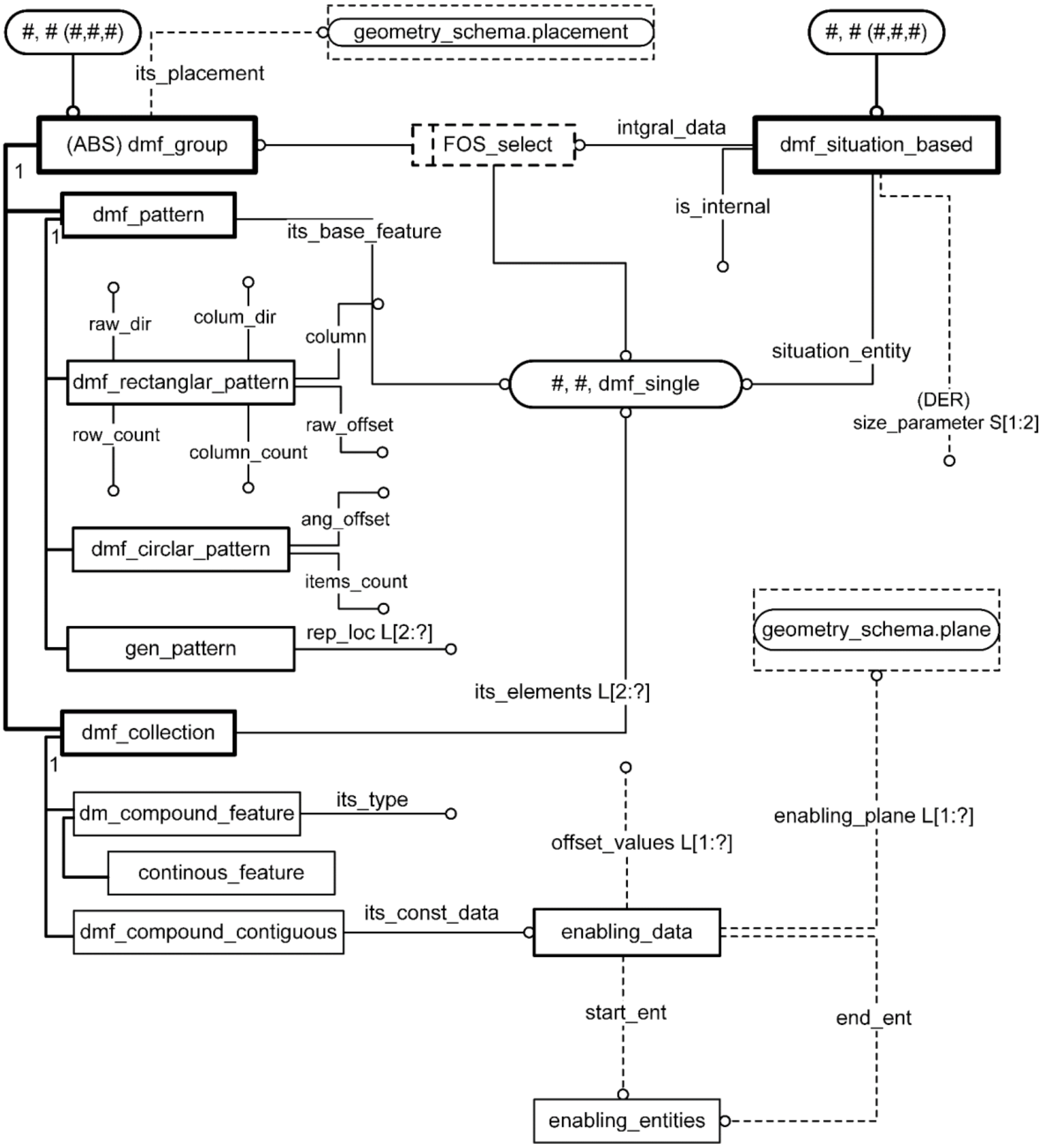


Figure 6-12: REIMS measurement feature group

2. The second subtype is the `dmf_compound_contiguous` entity that represents the compound-contiguous feature introduced in ISO 1101 (ISO 2012b). The compound-contiguous feature is used to define a collection of features specified by the in-between and all-over modifiers that are used with line and surface profile specifications. This feature grouping has no gaps, i.e. the included entities are all connected. Figure 6-15 shows examples of situations where the `dmf_compound_contiguous` entity is used.

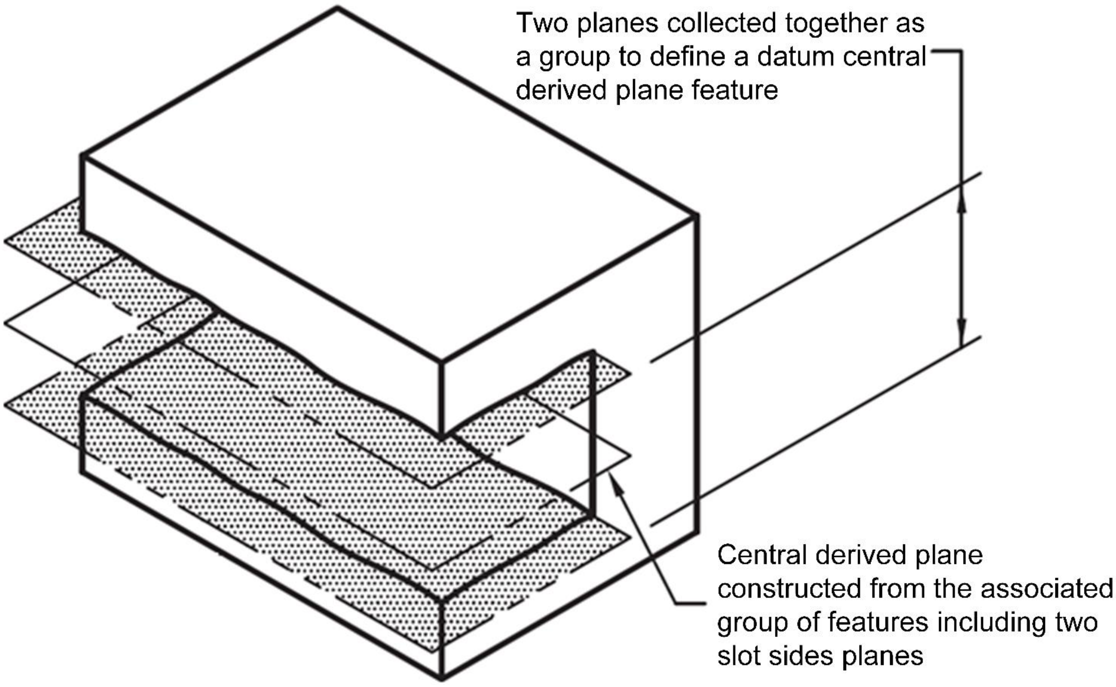


Figure 6-13: An example of a collection feature; Modified from (ASME 2009)

It should be stressed that defining `dmf_compound_contiguous` has some associated requirements that need to be represented to provide the necessary information for enabling the extraction and the construction of the related actual measured elements from the part physical surfaces. This data is represented as an `enabling_data` entity, which is referenced as an attribute of a `dmf_compound_contiguous` entity. For example, the profile tolerance specified in Figure 6-15 (a) requires the measurement to be achieved in a plan parallel to the datum 'A', such view-dependent information is represented using an `enabling_plane` attribute of the `enabling_data` entity as shown in Figure 6-12. The measurement-

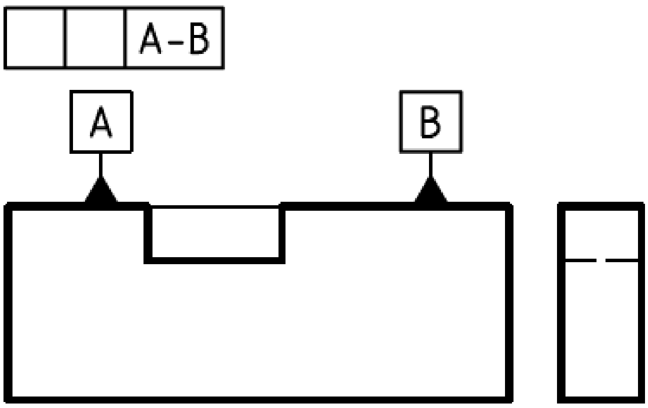
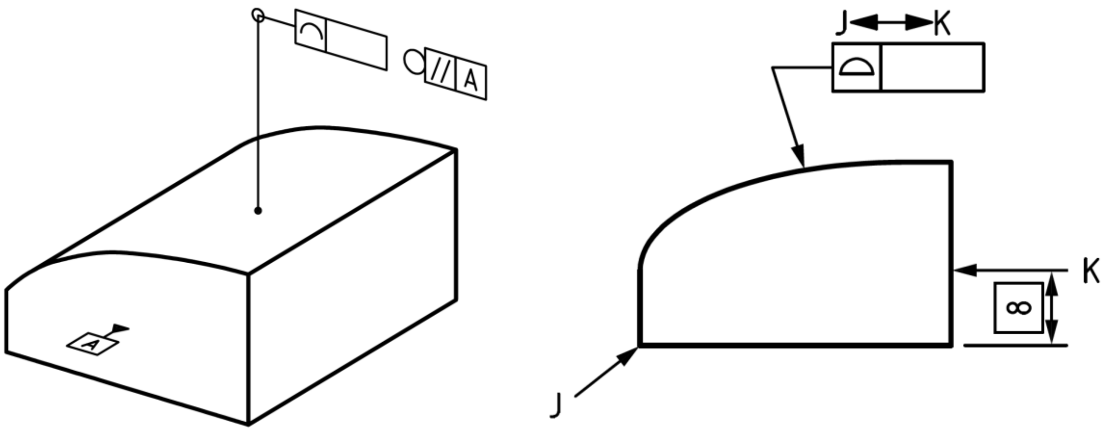


Figure 6-14: An example of continuous feature (ISO 2011a)



(a) (b)

Figure 6-15: An example of `dmf_compound_contiguous` feature (ISO 2012b)

planning algorithm uses the intersection plane data while constructing measurement paths for extracting actual `dmf_compound_contiguous` feature data. The measurement paths are constructed by offsetting this plane along the specified surface and calculating its intersection profiles with a part boundary as illustrated in Figure 6-22. In addition, the `enabling_data` entity can define the start and end entities of the `dmf_compound_contiguous` feature as the case for points 'J' and 'K' in Figure 6-15(b). Enabling plane data is used to represent both intersection and collection plane concepts presented in ISO GPS standards to define in-between and all-around modifier either in line or surface profile cases.

The `dmf_situation_feature` feature, shown in Figure 6-4, is a third subtype of the `measurement_feature` entity. The representation of the `dmf_situation_feature` entity is shown in Figure 6-12. This entity is defined to represent a feature of size (FoS) in REIMS and is mainly composed of a situation feature and a size parameter. The `dmf_situation_feature` entity enables the measured surfaces of a FoS to be directly linked to the size parameter and the situation feature defines the FoS. It is noteworthy that this entity should not be defined as a subtype of `dmf_collection.`

While such a relationship would allow REIMS to represent cases such as those shown in Figure 6-13 it would not allow FoS that consists of a single measurable surface such as hole feature and its axis as a situation element to be represented. Consequently, `dmf_situation_feature` can reference a `dmf_group` or `dmf_single` integral feature for its extraction. This entity reflects the fact that FoS is defined by the position and orientation of its situation or derived element and its size parameter. The dmf_situation_feature entity allows the explicit specification of the size parameter. This entity also specifies if the FoS is internal or external as shown in Figure 6-12.

6.3. Measurement operations

As previously discussed in subsection 4.2.4, ISO GPS introduced the operation concept to reflect the nature of measurement activities used to obtain different feature types. The REIMS data model follows the same philosophy by representing the different measurement operations as subtypes of the measurement_workingstep entity Figure 6-16 shows the inheritance tree of measurement_workingstep and its subtypes. The inheritance tree gathers the data related to setting the parameters of both measurement equipment and sensor under resource_dependent_operation entity. This entity is named as such to stress the fact that all other measurement operations in the REIMS data model are resource independent. It should be noted that the extraction operation is defined in a technology specific manner but not directly linked to a specific resource type.

Operator-dependent operations are modelled in the measurement_workingstep inheritance tree to allow for representation of the instructions that are provided to support the measurement operator in manual tasks. Using a hard gauge or a linear measurement instrument and recording a specific instrument reading are examples of such manual actions that could be carried out by the measurement operator. Other operation definitions have been listed separately in the inheritance tree of the measurement_workingstep entity as they can be performed manually or automatically, examples are clean and move_to entities.

Feature-based measurement operations are defined in association with nominal or actual measurement entities as inputs and are referenced by actual measurement entities that are affected by the operation definitions. A measurement operation can be associated with a complete part, a portion of a part or specific feature on a part. In fact, one of the design principles followed in REIMS is to relate each resulting actual measurement feature to a specific measurement operation, as this measurement operation represents, in reality, the actual conditions by which the actual measurement feature attributes are obtained. The consequence of implementing this principle is that more than one actual feature could result from one measurement operation definition, and hence multiple actual features could refer to a single measurement operation. Therefore, the interrelations between different types of measurement features are

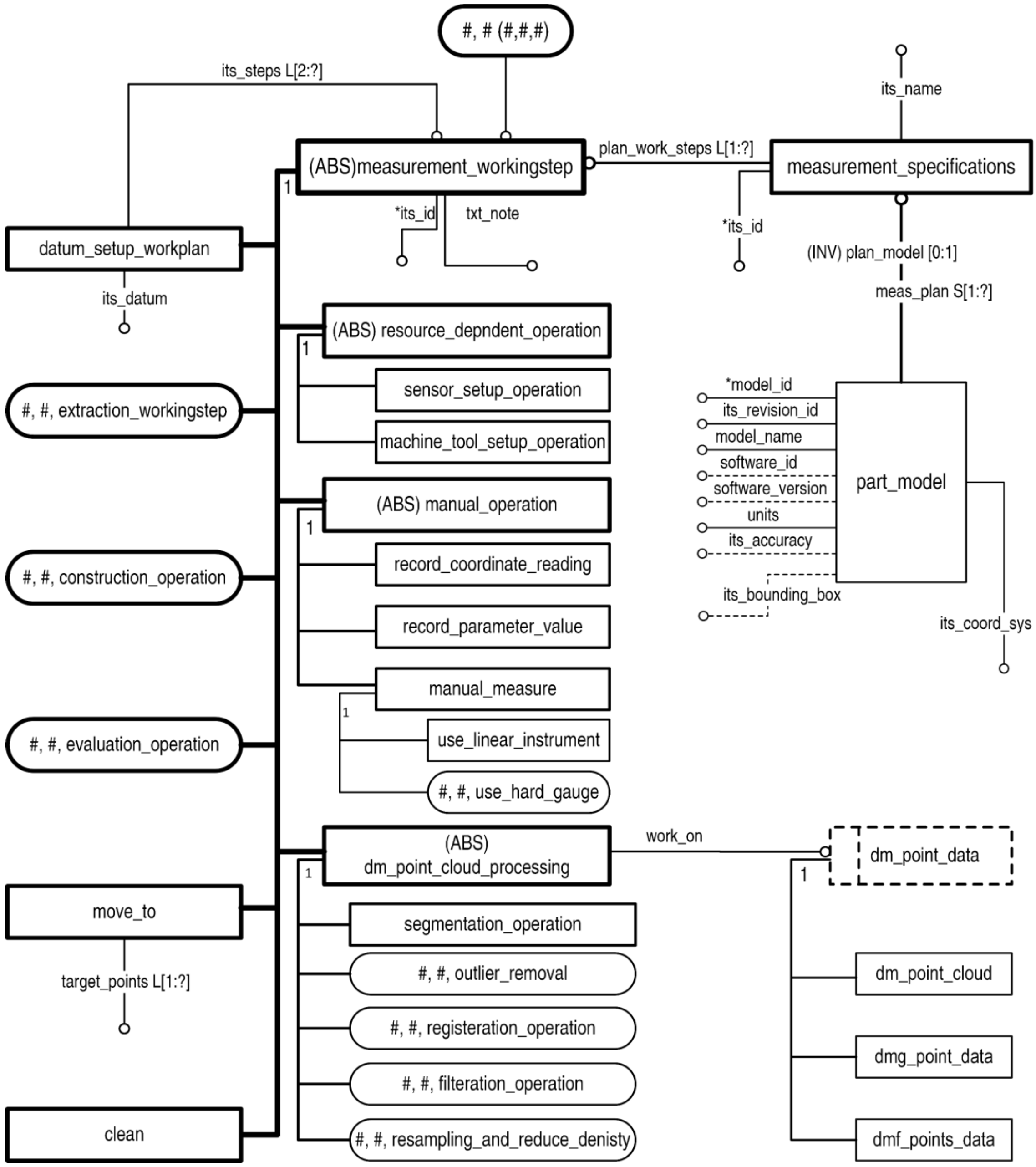


Figure 6-16 REIMS measurement workingstep

established through the measurement operations. For example, an `extraction_workingstep` entity is an operation that may be defined to work on a nominal integral entity to output a point cloud actual data. This operation can be applied many times on the same input feature to result in different actual point data in each run due to the inherited errors and uncertainties in the measurement process itself. It should be noted here that nominal features are seen in the REIMS data model as being an optional attribute in measurement operations to accommodate for reverse engineering requirements.

6.3.1. Extraction measurement operation

Extraction_workingstep is defined to represent a feature-dependent measurement operation that is deployed to obtain information about boundary surfaces of a manufactured part using a specific sensor technology. This measurement operation works on a dmf_nominal_integral feature where design data is available, or this measurement operation can be manually defined based on the available physical part in reverse engineering scenario. The output of this measurement operation can be represented in the form of a dmf_extracted feature defined by its dmf_point_cloud attribute. Figure 6-17 shows the extraction_workingstep representation and its inheritance tree in the REIMS data model. The figure also shows that the extraction_workingstep requires an optional extraction_requirement entity to be referenced as its_requirements attribute.

The extraction_requirement entity is defined to hold additional data that may be necessary for the complete definition of extraction_workingstep within measurement planning systems. Figure 6-18 illustrates the extraction_requirement entity and its specified attributes. This entity may define a safety plane to be used during extraction operation for allowing approach and retract movements. In addition, an extraction_requirement entity can be used to hold the restrained_condition when specified with the free-state modifier according to ISO 10579 (ISO 2013a) as shown in Figure 6-19.

The restrained_condition entity can represent the data specified for fixing an inspected part in position; this can be defined by tightening specifications or a datum simulator data that is calculated based on different datum boundary modifiers. The datum simulator size can be specified flexibly by using the mating_size entity. The part fixation can be specified for a maximum of three different datums. Furthermore, an extraction_requirement entity can limit the extraction operation to a specific cross section or area to cope with situations where a restricted design specification is defined. For example, specified tolerances per length or area units and target areas specified for datum definitions. Figure 6-20 shows two examples of the restricted application of the design specification.

The specified_area entity is defined to accommodate the restricted tolerance application or for the definition of datum targets. The enabling_data entity may be used with the specified_area entity to specify the direction of the first-dimensional

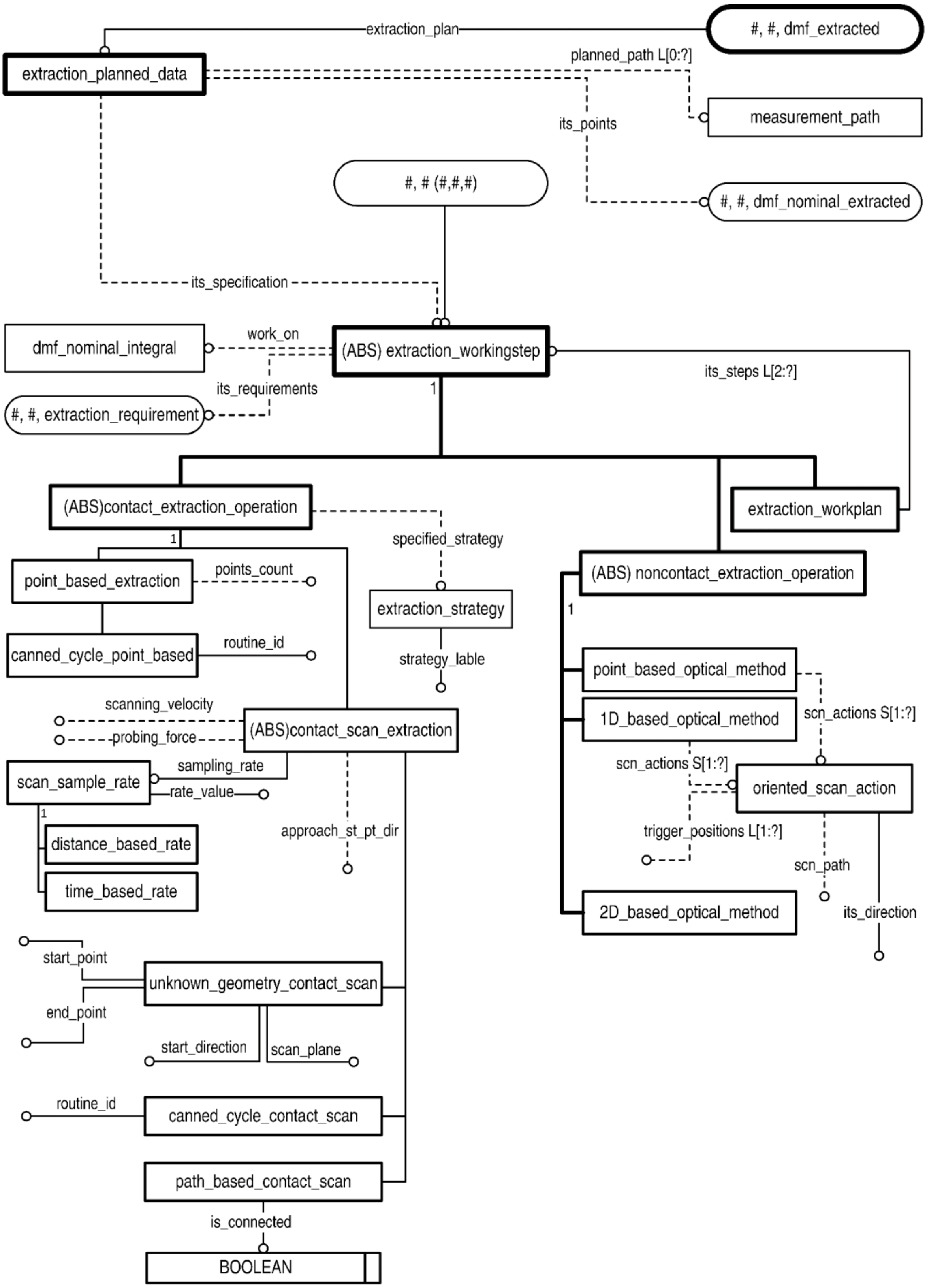


Figure 6-17: REIMS extraction workingstep

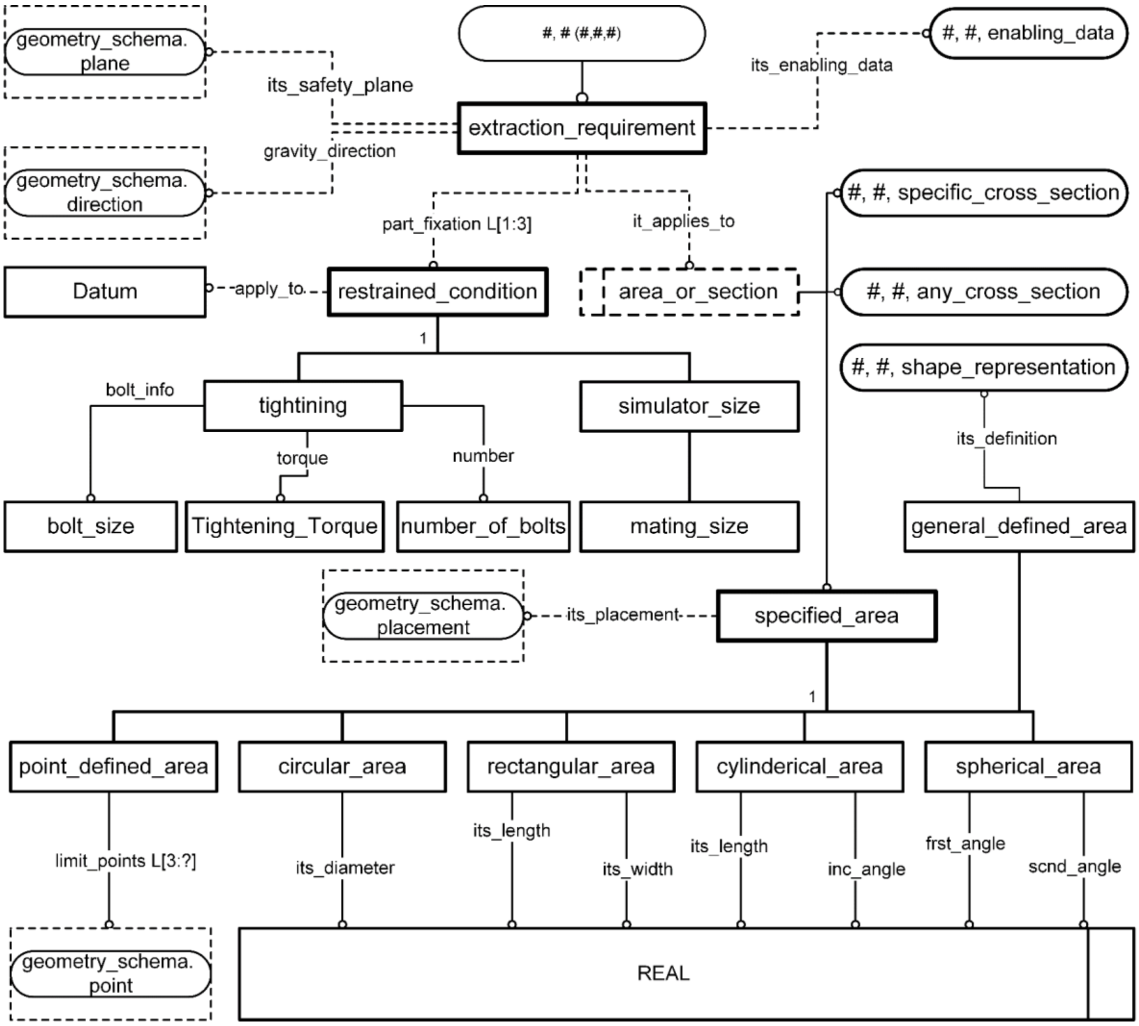
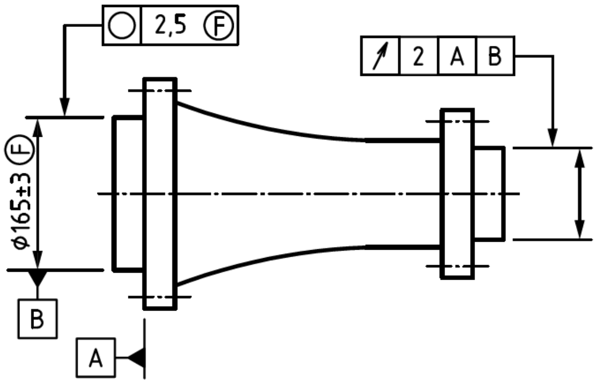


Figure 6-18: REIMS extraction_requirement entity and its attributes

parameter of an area. In addition, the `extraction_requirement` entity may reference `enabling_data` entity, represented in Figure 6-12, to hold view dependent extraction or tolerance zone information to capture the semantics of the design specification. Figure 6-21 shows an example of a case where the design specifications require enabling data for the extraction operation. Figure 6-22 shows an applicable example of how measurement applications use the enabling features to construct extraction section lines for dealing with view-dependent specifications.

As previously shown in Figure 6-17, there are three subtypes of the `extraction_workingstep` entity. These subtypes of the `extraction_workingstep` entity are defined to reflect different measurement technologies that can be used to get information from physical part surfaces. The `contact_extraction_operation` entity is defined to represent the contact measurement technology using contact probes on machine tools, CMMs or robots.

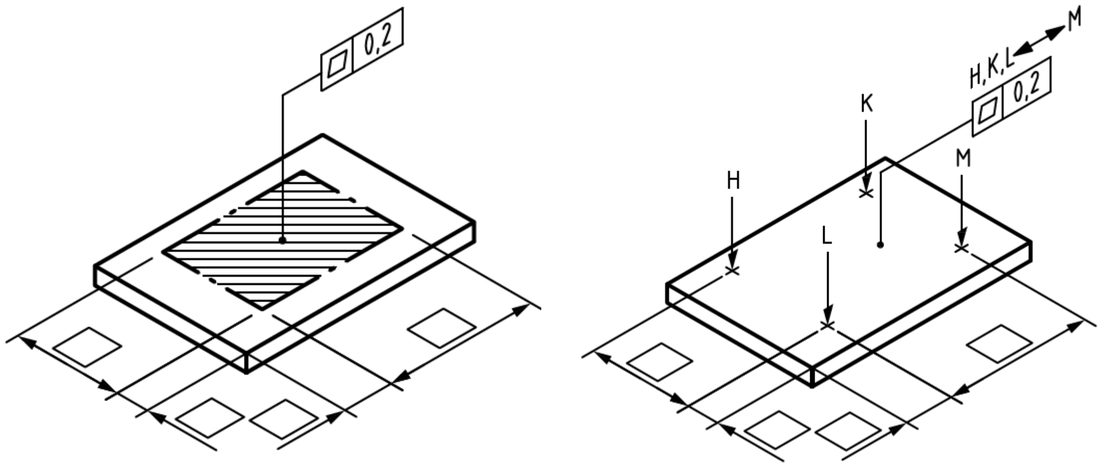


ISO 10579-NR

Restrained condition: The surface indicated as datum A is mounted (with 64 bolts M6 tightened to a torque of 9 N.m to 15 N.m) and the feature indicated as datum B is restrained at the corresponding mating size

Figure 6-19: Restrained condition as specified in ISO 10579, (ISO 2013a)

Contact measurement technology has two different mechanisms for extracting data. The first mechanism is through defining a number of points and their positions for contact on each feature; this scenario is represented by `point_based_extraction` subtype entity. These points are generated based on a specified strategy by the planning system as described in Figure 3-17 and Table 3-1. The second mechanism is to define scanning traces and sampling rates for each feature according to a predefined measurement strategy; this scenario is represented in the REIMS data model by `contact_scan_extraction` entity as shown in Figure 6-17. The `scanning_velocity` and `probing_force` attributes are defined for contact scanning



(a) (b)

Figure 6-20: Restricted application of a design specification (ISO 2012b)

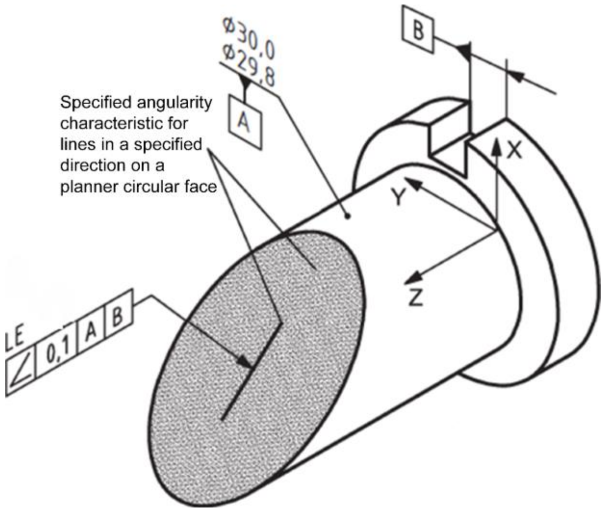


Figure 6-21: Specification requirement for enabling data; Modified from ISO/DIS (2012)

extraction operation as these parameters affect the final measurement results as reported by Pfeifer and Napierala (2000). These attributes are specified as being optional as they may be initialised, if not defined, by the default values set by the measurement equipment parameters. Scanning of unknown geometry does not include a specified `extraction_strategy`, and hence the `extraction_strategy` entity is defined as an optional attribute in REIMS. Scanning of unknown geometries requires information such as a start position, an end position, a start scanning direction and a scanning plane to guide the measurement equipment. The REIMS model also allows the contact-scanning strategy to be specified according to a predefined manufacturer specific canned cycle for specific geometries as shown in Figure 3-17.

An extraction operation can be defined for a measurement entity, which means that it can be related to a single feature or a group of features; for example, a specific characteristic can require the extraction of a pattern as its controlled entity. An extraction operation can be connected to different extracted data through referencing `dmf_group` whose single entities represented by `its_base_feature` attribute are `dmf_actual` features. In addition, a feature can have an extraction operation definition that consists

Figure 6-22: Construction of extraction lines using enabling data

of a list of other extraction operation definitions for lower dimensionality geometric entities. An example of this is when defining the extraction of a cylinder as a set of circle extractions along the central axis of the cylinder or to define the extraction of a plane as a set of line traces extraction. As shown in Figure 6-17, the REIMS model introduces the `extraction_workplan` that can hold a list of `extraction_workingstep`(s) to relate a child list of extraction information to the single parent measurement feature. Thus, a cylindrical feature can be related to extraction information of curve traces defined on its surface in addition to the resulting actual data. This design strategy enforces the necessary flexibility to locally or globally process the extracted data using the `extraction_workplan` entity. Local evaluation can be exemplified by evaluating the local centre of a specific extracted circle on a cylinder while a case of global processing is the evaluation of the fitted cylinder for all of the related data points.

The design of the REIMS data model considers that the `extraction_workingstep` definition is providing the necessary information for sampling and path planning algorithms in measurement planning systems to process the underlying geometries of CAD model and the specified measurement strategies and a number of point data. The design provides `extraction_planned_data` as a container to hold the resulting `dmf_nominal_extracted` and `measurement_path` data as shown in Figure 6-17. This entity refers to the `extraction_workingstep` as the specifications based on which it has been recognised. Despite the overall philosophy of REIMS to reduce human initiated uncertainty, this relation is set as optional to allow extraction data to be defined manually. This is to support the current industrial practice of defining extraction data based on experience; this should be discouraged as manual definitions are considered as a source of variability in measurement phase. The `dmf_extracted` measurement feature references the `extraction_planned_data` entity as it includes the actual information sent to a measurement programming stage for controlling measurement equipment to carry out the extraction operation. Figure 6-23 illustrates this information flow of REIMS entities of extraction operation between various CAx systems. Measurement path can be represented by the `path` entity defined in STEP AP238 (ISO 2006b), or by simply using a list of successive point coordinates.

Non-contact extraction technologies, on the other hand, are represented by the `noncontact_extraction_operation` entity. The subtypes of this entity are classified based on the optical dimensionality of used optical technology for the extraction process. For example, `point_based_optical_method` is reserved for the

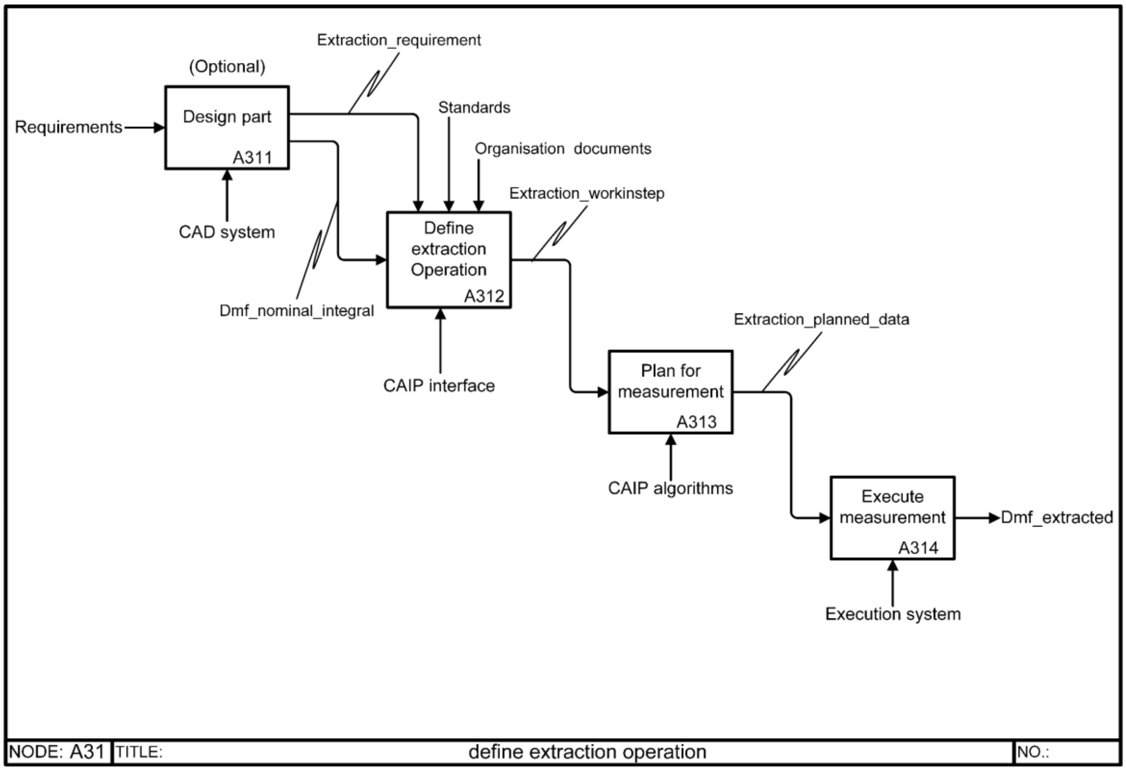


Figure 6-23 Information flow of extraction operation data between CAx systems

representation of optical sensors that are measuring in a point-based nature such as laser triangulation sensors that project a laser point toward the workpiece or laser trackers. The `1D_based_optical_method` entity represents laser triangulation sensors that project a scanning line on the workpiece physical surface for extraction. Finally, `2D_based_optical_method` is defined to represent the optical measurement by camera-based systems. In Figure 6-17, point-based and line-based scanning technologies are referencing a set of `scanning_action`(s) as an attribute that defines the scanning direction and path for both scanning mechanisms in addition to triggering positions only for point-based scanning mechanism.

6.3.2. Point cloud pre-processing measurement operations

In reverse engineering, it may be necessary to modify acquired data by different scanning technologies for preparing the extracted data for meshing or surface construction. The acquired data through scanning techniques can include outliers, spikes or noise information that needs to be eliminated as this can affect the final shape construction; this point data is also unordered by nature. The pre-processing operations work on `dmf_general_extracted` features and result in processed `dmf_general_extracted` measurement features. The REIMS data model defines outlier_removal, resample_and_reduce_denisty and registeration_operation measurement operations to satisfy pre-processing requirements of the collected measurement data in reverse engineering applications or normal conformance checking application as needed.

The noise reduction operation is used to remove outliers and spikes from the extracted point data. Noise reduction is based on statistical calculations of the relative distances between points. This operation then removes points outside allowed limits that are defined based on multiples of standard deviation. This process is captured in the outlier_removal measurement operation shown in Figure 6-24.

Unordered point data can be ordered when necessary through the resampling_and_reduce_density entity represented in Figure 6-25. The ordering step can be based on different criteria such as relative angle, edge length, aspect ratio and target point count. Subtypes are defined to accommodate these criteria as shown in Figure 6-25. Different criteria are used to define which cells in a point cloud are to be removed and which are not. For example, the angle criterion uses points' normal vectors information to remove points whose normal vectors are more than a specified angle from the scanning direction. The aspect ratio criterion removes points based on the ratio of the longest edge length of a cell to its shortest length. The edge length criterion removes points based simply on a specified cell length.

The resampling_and_reduce_density entity is defined not only to order point data but also for reducing the collected point density through target_pts_count subtype. This sub-entity specifies a lower total target point number that is used in reducing the original point cloud density. In Figure 6-25, the avoid_gaps Boolean attribute forces applied algorithm not to eliminate any point that may cause a large gap or hole in the resulting processed data. It is noteworthy that as good practice, these processing steps should not be applied if the checking of product conformance is the final goal as this processing causes the originally acquired point data to move from their original position or removed to satisfy the resampling criteria. The maximum movement can be recorded back in the max_deviation attribute to the processing system to give

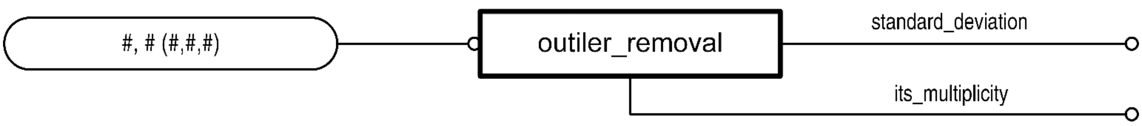


Figure 6-24: REIMS noise reduction measurement operation

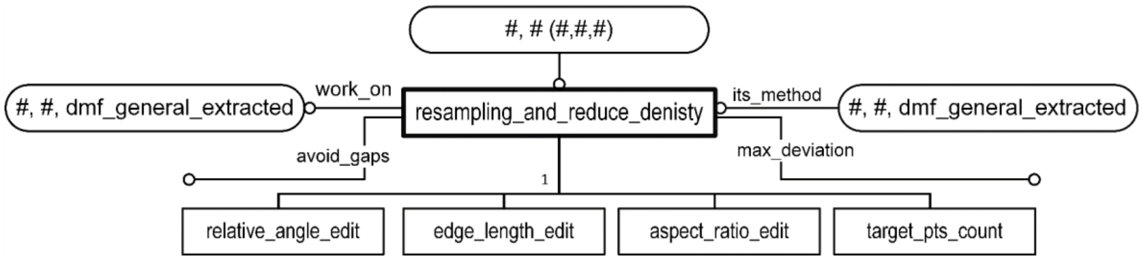


Figure 6-25: REIMS resampling processing measurement operation

an indication of the final loss of accuracy; this can be the average or maximum movement based on the processing system settings.

A registration operation is used when extracted data of a part is collected using different scans with in-between sensor or workpiece reorientations. Registration operation aligns all the scanned data together using some reference point that is determined manually or using pre-established targets. Figure 6-26 shows the registration measurement operation as defined in REIMS. The `registration_operation` entity works on two different `dmf_general_extracted` features.

The `registration_operation` outputs a `dmf_general_extracted` entity that is the result of the alignment process of the two input sets of data. This operation is carried out in two steps: a coarse registration step followed by a fine registration step. In coarse registration, some selected mapped points or target features are used in the two processed scanned data for enabling the alignment evaluation. Two subtype entities are

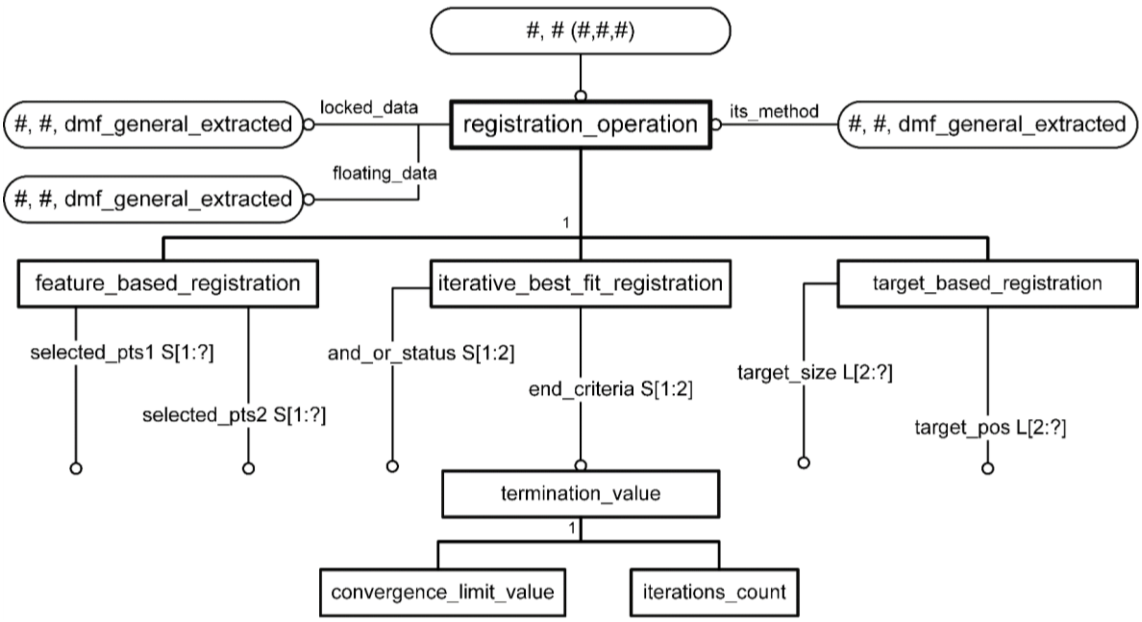


Figure 6-26: REIMS registration measurement operation

defined to represent the coarse alignment process; they are feature_based_registration and target_based_registration sub-entities. The first entity defines the corresponding selected points in both data sets while the second defines used spherical-target size and position. A segmentation process is required to separate point data related to defined targets in order to evaluate the targets' centre point. On the other hand, the fine registration step is based on an iterative best-fit method that includes the definition of one or two termination criteria with AND or OR relationships.

6.3.3. Filtration measurement operation for roughness and profile assessment

A filtration operation is a processing measurement operation that works on extracted data to separate some unnecessary information from the perspective of a specific measurement scope. Figure 6-27 shows an illustration of the filtration concept to remove unnecessary information. This process is commonly applied before the evaluation of form or roughness characteristics. The filtering_operation entity represents this process in REIMS and works on a dmf_extracted actual measurement entity and outputs dmf_filtered actual measurement feature as shown in Figure 6-28.

It should be noted that the REIMS model separates outliers-removal and noise-reduction operations from filtration operation definitions. This is to reflect the fact that the former are pre-processing steps on a directly gathered measurement data, whereas the latter are processing steps that serve a specific purpose required by the measurement

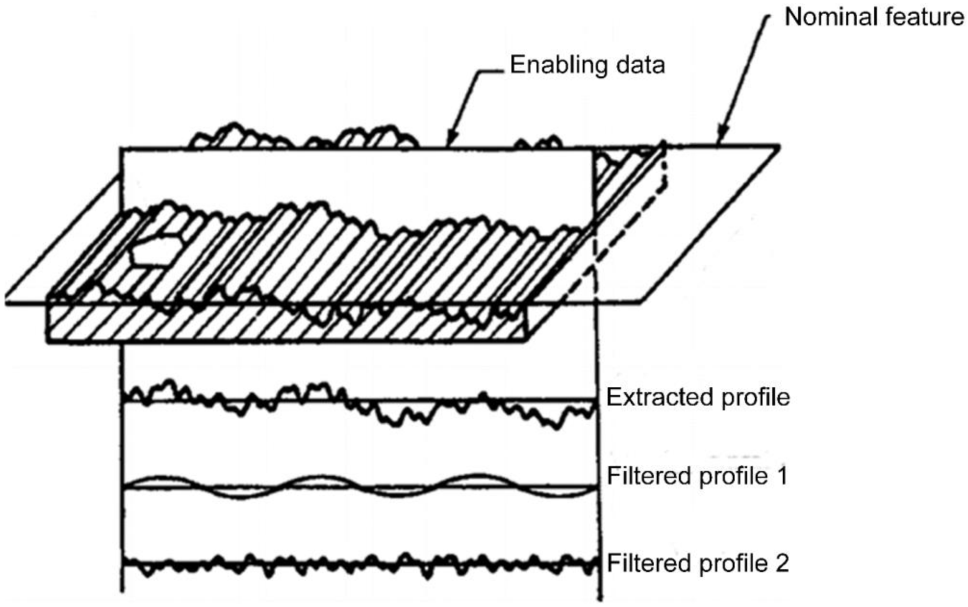


Figure 6-27: Filtering operations; Modified from (Muralikrishnan and Raja 2009)

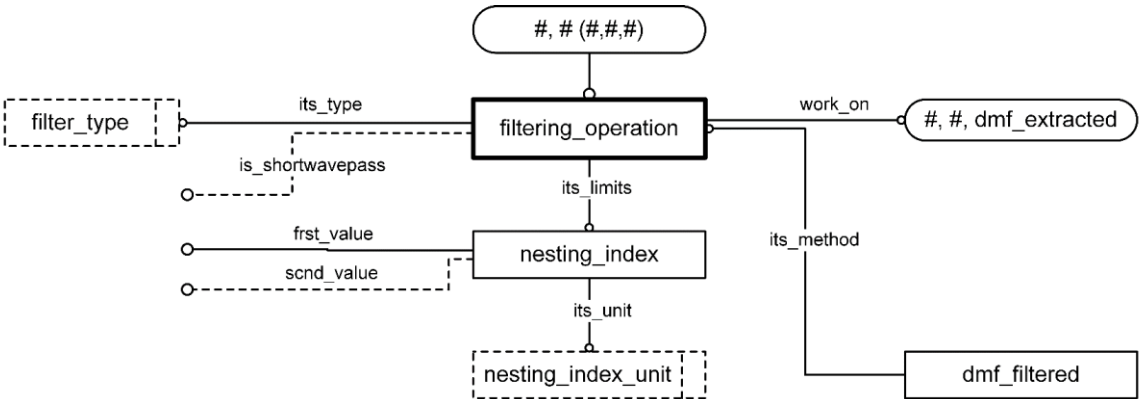


Figure 6-28: REIMS filtering measurement operation

process. Examples of such specific purposes include calculating the roughness or form profiles from extracted data. In addition, as indicated in Figure 4-21, the applied filter is essential to be defined during measurement planning phase as used filter parameters affect final evaluated measurement results. The `filtering_operation` entity includes a `filter_type` as an enumeration datatype attribute to enable the identification of used filter according to the measurement purpose. Examples of filter types include Gaussian, Spline and Wavelet filters. A full list of standardised filtering methods and their related standard documents can be found in appendix E of ISO 1011 amd1 (ISO 2012a).

The `is_shortwavepass` Boolean entity is used to identify if the applied filter is a short-pass or long-pass filter. This attribute is optional, as it is only needed when a single index value is indicated; in other words, if it is not a bandwidth filter. If the filter is a bandwidth filter then the two `nesting_index` value attributes are required; the first value should record the larger value. The `nesting_index` entity is the limit of smoothness required by the applied filter. Each nesting index value should be accompanied by specific units. Examples of nesting index units are *mm* for linear profiles or undulations per revolution (*UPR)* for circular profiles in roundness evaluation. A full list of nesting indices for each filter type can be found in appendix E of ISO 1011 amd1, (ISO 2012a). Figure 6-29 shows the relationship between `dmf_extracted` and `dmf_filtered` measurement features through the `filtering_operation` definition.

6.3.4. Construction measurement operations

Construction of ideal geometric entities may be required during the analysis of measurement data for the evaluation of an actual specification value. Construction steps

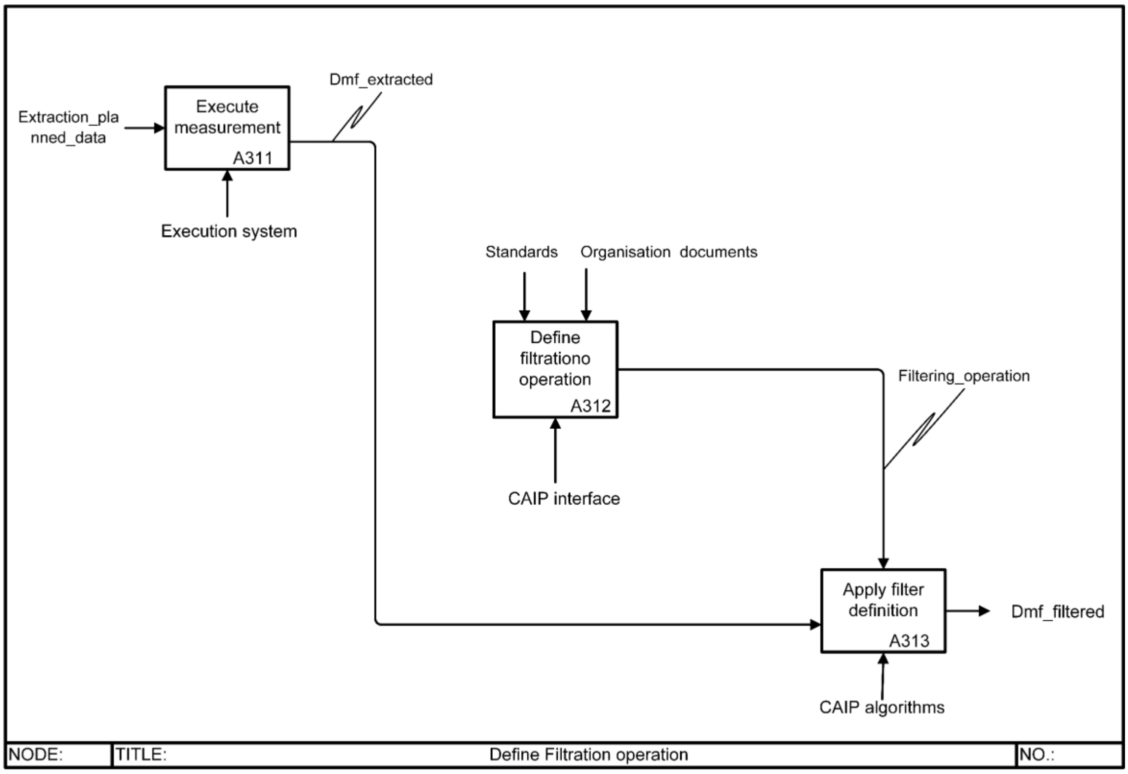


Figure 6-29: `dmf_extracted` and `dmf_filtered` relation through the `filtering_operation` definition

use other actual or nominal features to obtain the definition of a constructed new feature. REIMS specifies `construction_operation` as an abstract entity inherited from `construction_workingstep` as shown in Figure 6-30. The `construction_operation` is a measurement operation that is applied to obtain actual features from other features, either only actuals or actuals and nominals, based on specific construction criteria. The input to the construction operation is a unique list of actual features that may also include nominal features. There is a minimum number of actual features required for the construction of a specific type of feature. For example, to construct a line at least two pieces of information are required; either two points or a point and a direction. With similar logic, to construct a circle at least three points are necessary.

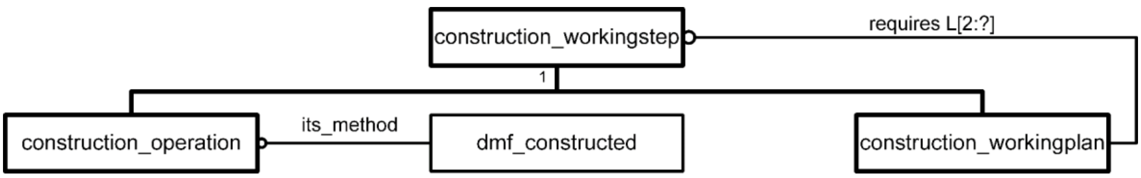


Figure 6-30: REIMS construction workingstep, operation and working plan

The resulting measurement feature from a construction_operation is dmf_constructed actual measurement feature. The construction_operation works on entities that are specified in the subtypes of construction_operation entity, as the input data varies with the type of the applied construction_operation. Different types of construction operation are represented as subtypes inherited from construction_operation abstract supertype entity. These subtypes include, for example: transform; projection; intersection; offset; tangent; tangent through; and, other construction methods. In practice, the construction operation may require the definition of other construction operations to enable its completion. For example, the construction of a mid-line between two bounded lines in a 2D plane requires the construction of two lines between the end points of both lines and, then, the final mid-line is that line connecting the mid-points of the previously constructed lines. The construction_workingplan entity is defined in REIMS to represent this situation as shown in Figure 6-30.

(i) Fitting construction operation

The fitting operation is a measurement operation that is used to construct an ideal geometric feature out of an actual point data. The fitting operation is known as the association operation in ISO GPS definitions and is used mainly to construct reference elements to which actual data are evaluated. There are different types of fitting; in addition, the fitting can be constrained or unconstrained based on the problem in hand. Figure 6-31 shows different types of fitting problems and base features that are commonly used within measurement applications. REIMS defines best_fit_construction entity to represent the association operation. The best_fit_construction entity works on one or more measurement_feature(s) to produce one or more dmf_associated measurement features. If more than one measurement_feature is to be considered by a fitting method, this would mean that there are positional or orientational constraints between the features that should be respected by the fitting solution.

Figure 6-32 show the REIMS representation of best_fit_construction measurement operation and its specified attributes to reflect these requirements of the feature fitting step. The input entity to the fitting operation is relaxed to be a measurement_feature entity as it may be either dmf_extracted, dmf_filtered or dmf_group. The fitting operation requires the definition of base geometry to be fitted to point data and an association method. Base geometry can be, for example, a line, a

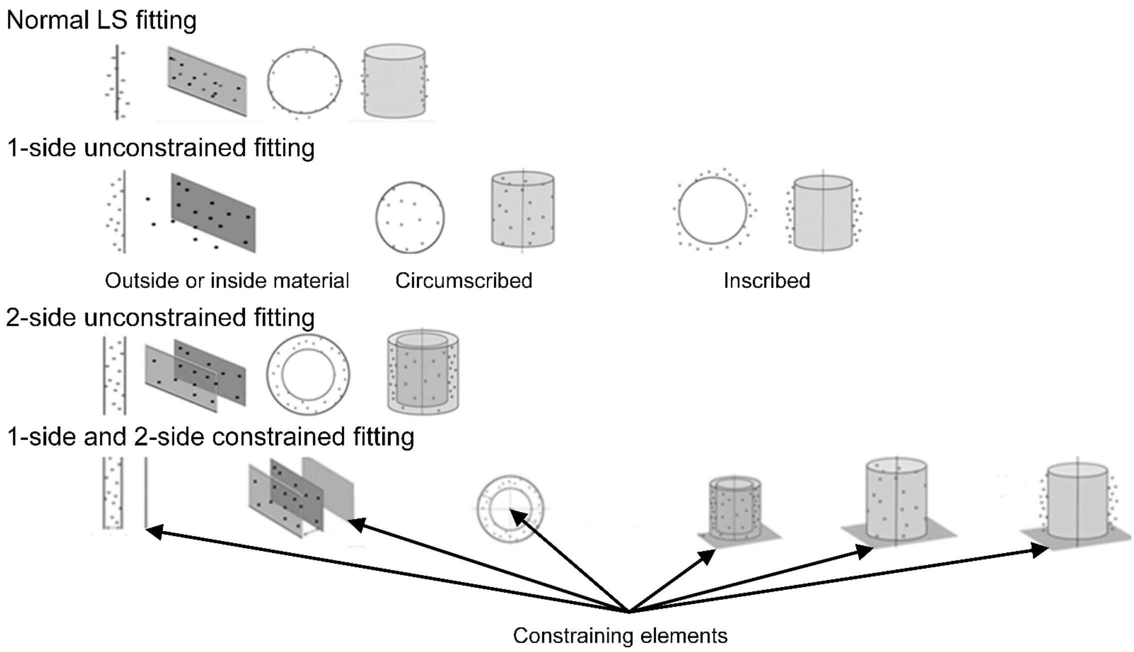


Figure 6-31: Classification of feature fitting process, modified from (Mohan *et al.* 2015)

circle, a plane or a cylinder as shown in Figure 6-31. There are different association methods that can be used for a specification type and a base geometry. In Figure 6-32, base geometry and association method are specified as attributes of the `best_fit_construction` entity. The `base_geometry` attribute is an enumeration data type to define a nominal feature to be constructed. In fact, some cases require that the `base_geometry` entity reference a different geometric definition from this used in nominal geometry of the extracted feature, such is the case where datum targets with contacting features (CF) modifiers are fitted to extracted data of different base geometry type; this will be discussed further in subsection 6.4.3.

The `assoc_method` attribute holds defined fitting criteria as defined in ISO1101/Amd1 (ISO 2012a). Table 6-1 shows association methods and modifiers used within the design specification as presented in ISO1101/Amd1 (ISO 2012a). Rules can be defined for restricting the allowable fitting criteria based on the fitted `base_geometry` and applied specification types. Recently, researchers have begun to consider standardisation of the applied fitting methods in measurement practice according to the standardised definitions of specifications (Mohan *et al.* 2015; Vemulapalli *et al.* 2013; Mani *et al.* 2011); such studies can result in rules that can be used in measurement applications.

In Figure 6-32, the `fit_constraints` attribute is used if the association operation defines a constrained fitting problem. This attribute defines different kinds of

Table 6-1: Fitting methods and modifiers as defined in ISO GPS (ISO 2012a)

Modifier	Association method
C	Minimax (Chebyshev)
G	Least Squares (Gaussian)
X	Maximum Inscribed
N	Minimum Circumscribed
E	Constrained external to the material
I	Constrained Internal to Material

constraints, which are required relations between entities resulting from the fitting operation or between resulting features and other reference features. If the `constraining_feature` attribute is used, this should refer to a constraining reference feature. If this attribute is not used, the constraint then refers to the interrelations between features forming a group referenced by the association `best_fit_construction` operation. There are different types of constraints that can be applied such as `material_constrain`, `distance_constrain`, `angle_constrain` and `intrinsic_param_constrain` sub-entities in Figure 6-32.

The material constraint is specified with 1-side fitting problems where the fitted entities are required to be on the “in” or “out” sides of material represented by extracted data; planar datum fitting is a common scenario for this fitting type. It should be noted

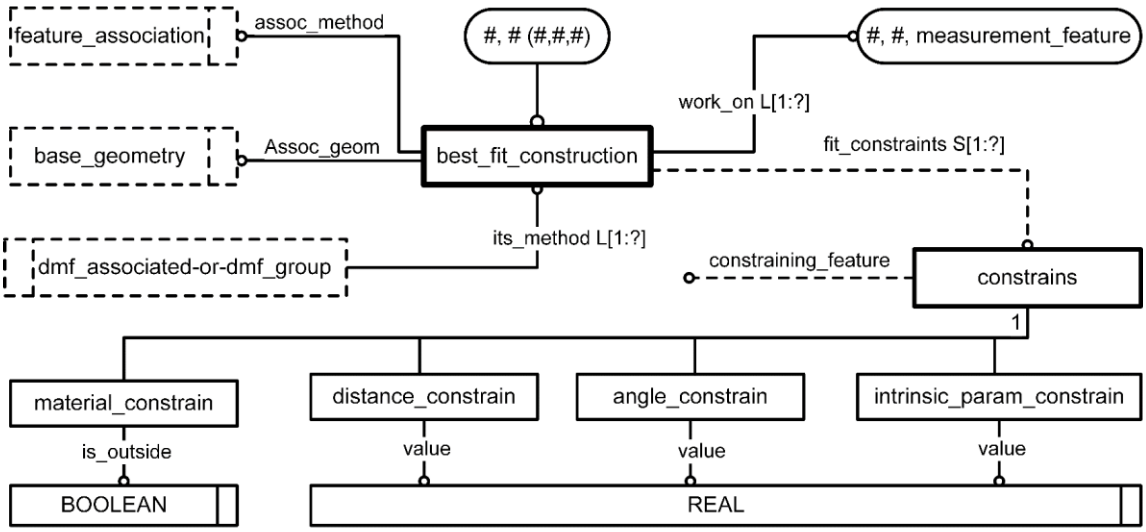


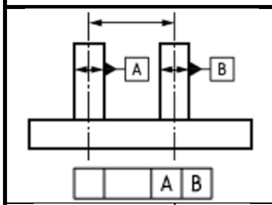
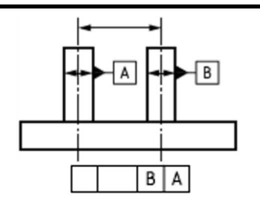
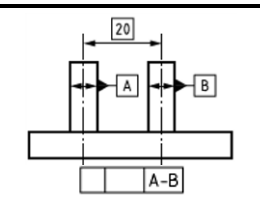
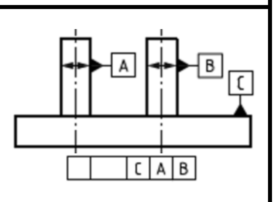
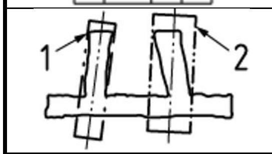
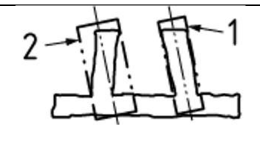
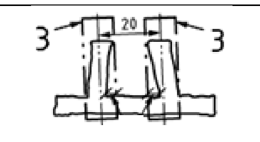
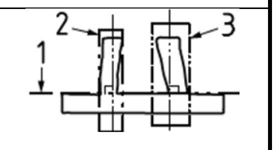
Figure 6-32: REIMS association operation

that no material constraints are required for the least squares (LS) fitting method. Distance constraint is specified where two geometric entities are required to be fitted while keeping a specified distance between them; normally, this distance is specified as a theoretical exact dimension (TED) in design specifications. The angle constraint is also a location constraint similar to distance constraints but denotes angular positioning rather than linear; parallelism and perpendicularity constraints are special cases of angle constraints. Size parameter constraints are used when features are constrained while their relating size parameter is required to be constant. It should be noted that these constraints, when being defined, are used during the evaluation of the reported associated feature. Hence, these constraints should be defined explicitly during the measurement process definition stage to ensure consistent results. Table 6-2 shows examples of how the specification can affect the unconstrained and constrained association results for datum-system establishment case in measurement.

(ii) Transform construction measurement operation

Transform construction is defined in REIMS to accommodate simple copy and move geometric operations in addition to the more complicated transformation geometric operations that can be applied to a specific base feature type. Transform construction operation is represented in the REIMS data model by `transform_construction` entity shown in Figure 6-33. The `transform_construction` entity references, as its attributes, the `base_feature` to be affected by the transformation, the definition of applied `transformation` and a Boolean to indicate if the base feature is kept after the transformation is applied. The `keep_original` Boolean attribute is thus used to differentiate copy and move construction methods.

Table 6-2: Unconstrained and constrained association; Modified from (ISO 2011a)

Case 1	Case 2	Case 3	Case 4
			
			

1 … Unconstrained association of single feature
2 … Constrained association of single feature with angle constrain with respect to 1
3 … Simultaneous constrained association of two features with distance constrain

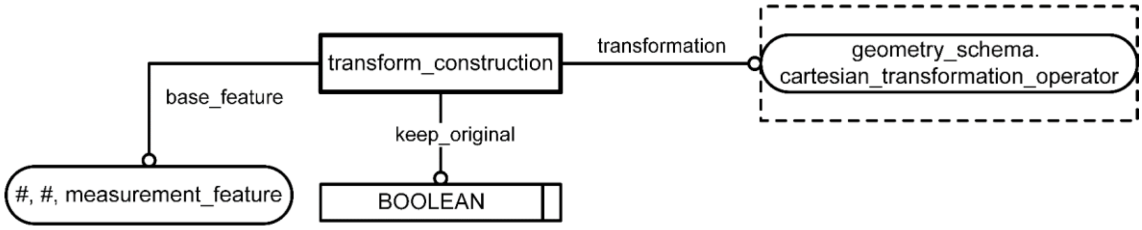


Figure 6-33: REIMS transform construction operation

(iii) Projection construction measurement operation

The projection operation may be necessary during the measurement analysis phase; for example, to associate a circle to the related extracted data, the points used in association need to be coplanar, therefore the extracted points are first projected to their fitted LS plane before the construction of a circle geometric entity can occur. REIMS represents these required measurement actions by introducing the `projection_construction` entity as shown in Figure 6-34. This entity has a projected feature and a projection feature as attributes. The `projected_feature` and the `projection_feature` can be points or lines that can be derived from a `point_reducible_feature` or a `line_reducible_feature`. Reducible features are reduced forms of other features that are represented by simple geometries such as points, lines or planes.

The reducible features are used in different construction measurement operations instead of their parent entities. For example, if the projected feature is a circle that is referenced directly, the resulting constructed feature is a circle, but if the projected feature is a circle referenced through a `point_reducible_feature` entity, then the resulting constructed feature is the projected centre point and not a circle. Referencing reduced features means that whatever the projected or the projection feature definitions, they are treated as points, lines or planes in the construction operation. Table 6-3 shows the returned feature data when a feature is referenced in its reduced form. This table is derived using information from standards such as ISO 17450-1 (ISO 2011h), and DMIS (ISO 2010c). Figure 6-35 illustrates the REIMS representation of these reducible

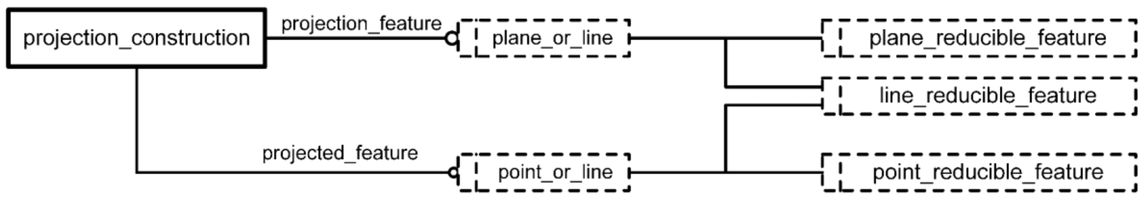


Figure 6-34: REIMS projection measurement operation

Table 6-3: Examples of reducible situation features

Original Feature	Reducible situation Features		
	Point	Line	Plane
Point	Point itself	-	-
sphere	Centre point	-	-
Cone	Apex	Axis	-
Ellipse	Centre between foci	From focus1 to focus2	-
Circle	Centre point	Normal of its plane	Plane of the circle
Torus	Centre point	Axis	Plane
Line	-	Line itself	-
Two parallel lines	-	Line	-
Cylinder	-	Axis	-
Plane	-	-	Plane itself
Two parallel planes	-	-	Plane
Two Symmetric Planes	-	-	Plane

features as select data types in the data model. Rules may be defined to restrict feature types; for example, to restrict the `projection_feature` to a `plane_reducible_feature` when the `projected_feature` is a `line_reducible_feature`.

(iv) Tangent and pass-through construction

Two construction operations are defined in REIMS to represent those features constructed, during measurement analysis phase, with a tangency or angular relations with other features. For example, `tangent_construction` entity represents those lines or circles constructed by being tangent to any two combinations of circle or line features. Figure 6-36 shows examples for constructing a line and a circle with tangency relations to other geometric entities. The optional diameter attribute is required when a circle is to be constructed as being tangent to two co-planar but not parallel lines to obtain a unique solution. On the other hand, `pass_through_construction` represents those features that pass through a specified point while respecting a tangency, perpendicularity or parallelism relation with another feature.

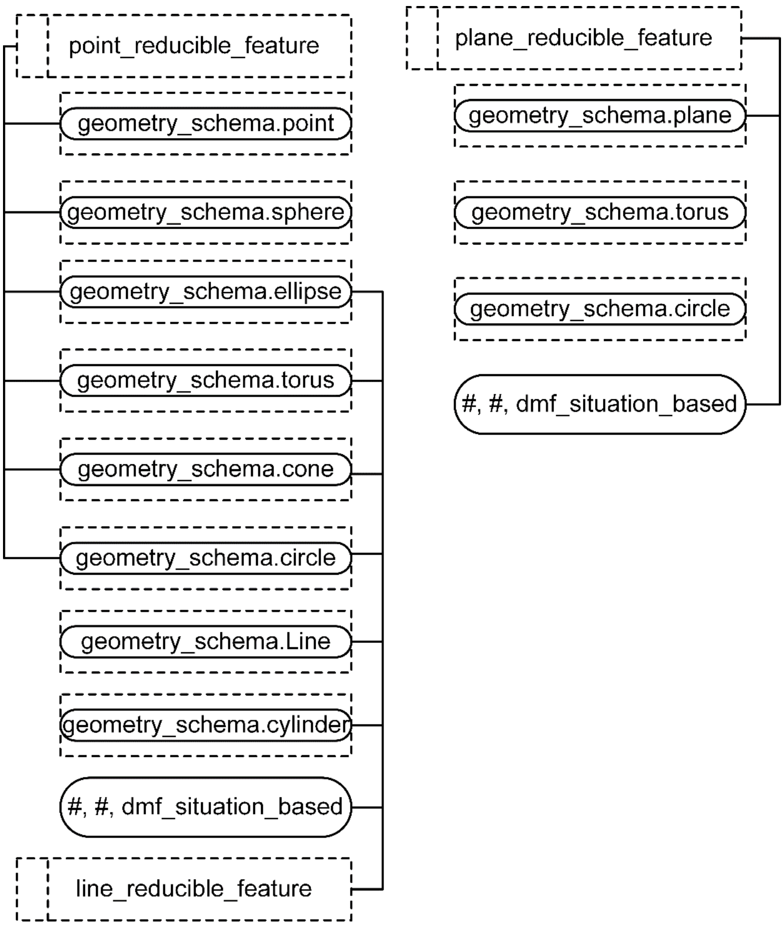


Figure 6-35: REIMS reducible features

Figure 6-37 shows an example of constructing a line and a circle that are both constrained to pass through a defined point and with a specified relation with other geometric entity. Figure 6-38 shows the REIMS representation of the pass-through construction. The `relation` attribute of `pass_through_construction` entity is an enumeration to identify the relation between the constructed entity and the feature defined `relating_feature` attribute. Many relating features can be specified when the `through_point` optional attribute is not specified. For example, a plane feature can

Figure 6-36: Examples of constructed features with tangency relations (ISO 2010c)

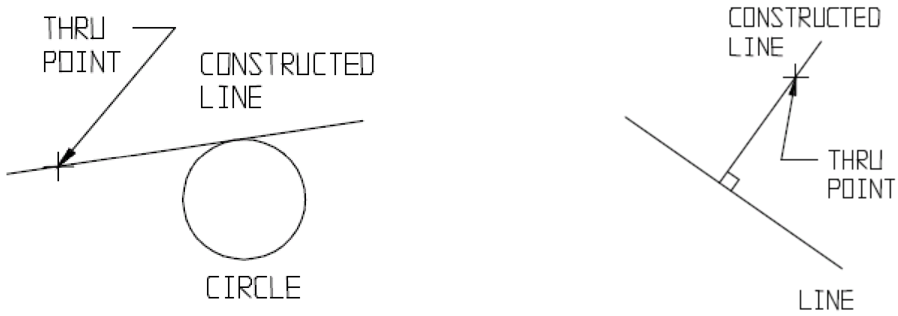


Figure 6-37: Pass through construction examples (ISO 2010c)

be constructed perpendicular to another plane and pass through a point that is not on the relating plane feature or it could be constructed perpendicular to two orthogonal planar features. Constraints can be defined to restrict the type of the `relating_feature` based on the type of the constructed feature and the defined `relation`. For example, if a line is to be constructed perpendicular to a relating feature; this relating feature is restricted to either a line or a plane. If a line is constructed to be tangent to a related feature, this feature is restricted to a circle feature. Line reducible features may also be used in this construction operation in place of relating feature definitions as appropriate.

(v) Offset construction

This measurement construction operation is used to offset a defined feature directly or indirectly. Offset operation can be specified directly by offset value and direction attributes. The offset operation can be defined indirectly by defining a set of `point_reducible_feature`(s) that are used to evaluate offset value and direction based on their geometric data. Figure 6-39 shows how REIMS specifies the `offset_construction` measurement operation to represent offset geometric operations.

(vi) Mid-construction operation

Mid-construction measurement operation defines an entity in the middle between two other defined entities. In a measurement application, it may be necessary to

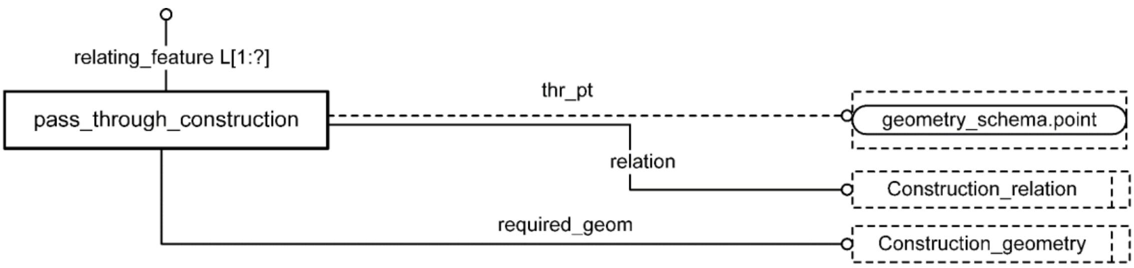


Figure 6-38: REIMS pass through construction operation

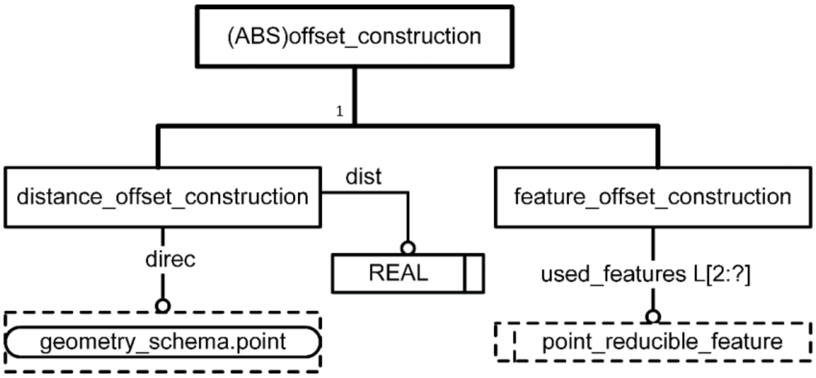


Figure 6-39: REIMS offset measurement operation

construct the midpoint of two points; this also applies for mid-line and mid-plane. Construction of derived measurement features from extracted data is one applicable example for using `mid_construction` operation. The REIMS data model specifies `mid_construction` operation as shown in Figure 6-40. Reducible features are also used in the construction operation in place of the point, line or plane features as in the example shown Figure 6-41.

(vii) Intersection construction operation

This measurement operation is applied to define a feature as being the intersection of two other features. The intersected features can be any of the subtypes of both `curve` and `surface` entities defined in the `geometry_schema` in STEP AP242 (ISO 2014a). An example of using this operation is when it is required to construct an extraction line during measurement planning by intersecting an enabling feature with nominal surfaces as shown in Figure 6-22. Figure 6-42 shows how REIMS specifies the intersection construction operation.

6.3.5. Illustrative example

An illustrative example is used to gather some of the introduced concepts in this chapter about measurement features and operations that are the core of REIMS data

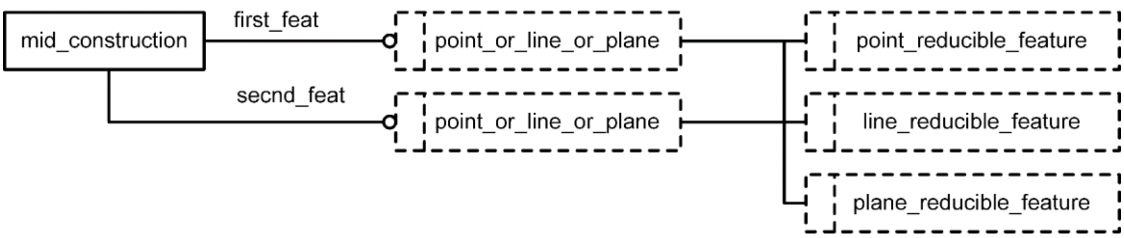


Figure 6-40: REIMS mid_construction measurement operation

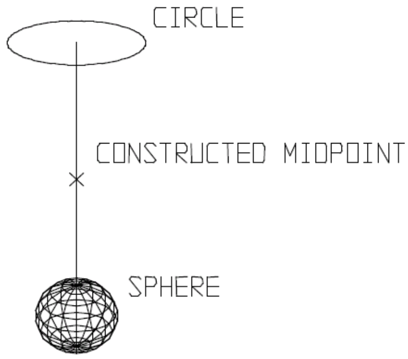


Figure 6-41: An example of use of reducible feature in mid-construction operations

model. Figure 6-43 shows a simple dimensional characteristic that needs to be evaluated. This characteristic is specified at a specific cross section that requires the definition of an enabling feature for evaluating its related extraction profile. As shown in Figure 6-43, the nominal features in this example are the conical surface and the planar surface from which the basic dimension is evaluated. These features are measured using a specified extraction operation. The standard measurement process definition according to the REIMS data model and the ISO 17450-3 (ISO 2014b) is composed of a set of operations to obtain different kinds of features as follows:

1. Define extraction operation for both conical and planar faces.
2. Define an association operation for the conical face to fit an ideal cone to the extracted data.
3. Obtain the derived situation feature of the resulted ideal associated feature; i.e. cone axis.
4. Define a construction operation for an enabling feature that is fitted to the extracted data of the actual planar face while being perpendicular to the associated cone axis and lie outside of the material.
5. Define a construction operation to move the enabling feature by a value equal to the TED and in the direction of the material.
6. Define an intersection operation to evaluate the extraction trace.

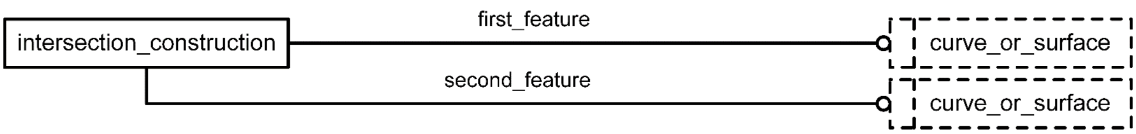


Figure 6-42: REIMS intersection measurement operation

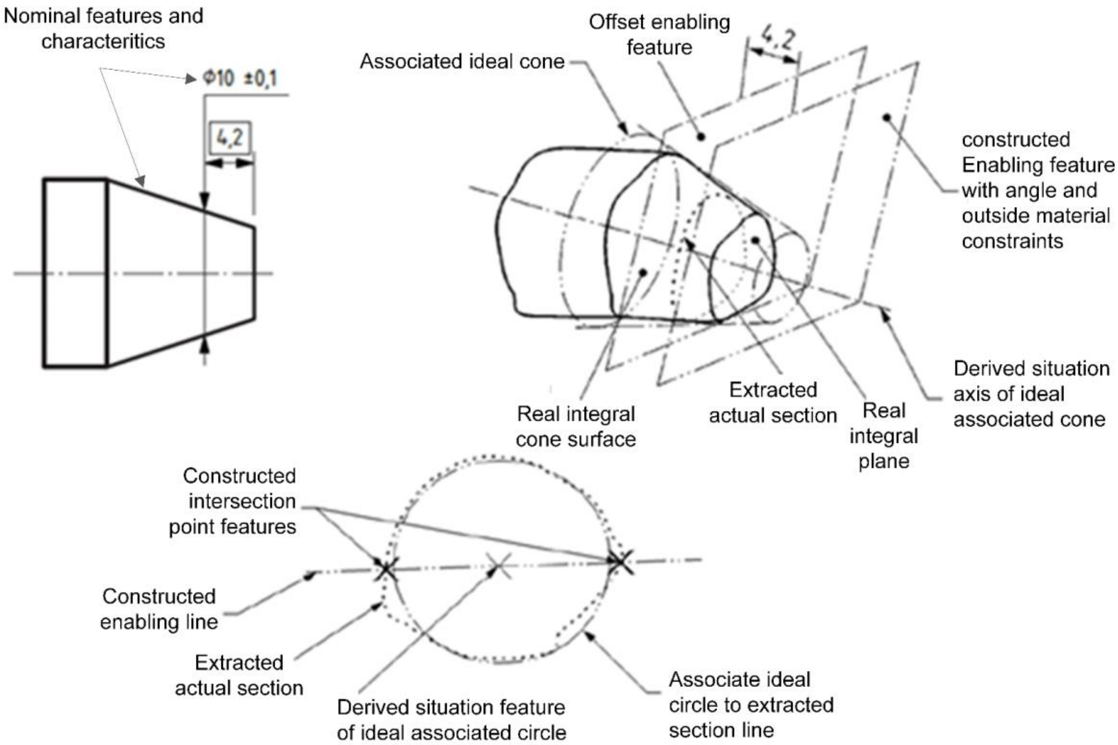


Figure 6-43: illustrative example of the measurement process definition; Modified from (ISO 2014b)

7. Define an extraction operation using the extraction trace evaluated in step (5).
8. Define an association operation to evaluate ideal circle represented by actual data and then to obtain its situation centre feature.
9. Construct a line that passes through the centre and is perpendicular to the situation axis of the ideal associated cone feature.
10. Define an intersection operation between the enabling feature in (8) and the actually extracted section profile to define two adjacent points.
11. Evaluate the distance between the two constructed points in step (9).
12. Compare the evaluated distance in step (10) with nominal and tolerance values specified by the designer.

The steps from (1) to (12) are the measurement process definition for the dimensional characteristics shown in Figure 6-43. The steps from (1) to (6) are used to ensure that the defined extracted trace matches the standardised specification definitions. This example indicates that the REIMS core data, which are measurement features and operations, can be used to define a measurement process completely. The data and attributes required for specifying the operation used through steps (1) to (12) are populated based on specified standardised rules or manually based on the experience of a standardised practice where the rules are not available.

6.3.6. Datum setup operations

Part coordinate systems are related to datum systems that are defined on a part. Part coordinate systems are established with respect to the machine coordinate system during measurement execution phase in a step known as part alignment. Part coordinate systems need to be established prior to any related measurement actions on features specified with respect to datum reference frames that define those part coordinate systems. The nominally defined features in the design stage specify nominal coordinate systems while the actual features extracted from the real part surfaces establish actual coordinate systems against which features' position and orientation are evaluated. The specification of datum setup operation is necessary as any error during this step will be propagated through subsequent measurements (Horsfall 2007). DMIS standard (ISO 2010c), defines three different types of datum setup methodologies. REIMS specifies these three ways to control the setup of the coordinate systems as shown in Figure 6-44.

The first method restrains coordinate system using previously measured or constructed features. REIMS defines the `feature_based_alignment` entity to represent this datum setup technique. The `feature_based_alignment` entity has a unique list of `alignment_by_feature` steps; the list holds one to three alignment steps. In each alignment step, a specified axis and, optionally, an axis origin can be aligned to a defined datum feature. In other words, the defined datum feature establishes this axis and the axis origin in the intended part coordinate system. For example, if the primary datum is a cylindrical feature and the z-axis is set to this cylinder, this means that the cylinder axis will be the z-axis of the resulting part coordinate system. In addition, if the z-axis and its origin are aligned to a plane feature, the plane normal would become the z-axis of the resulting coordinate system, and the plane becomes the zero position on this axis. It should be noted that an axis origin could only be defined for the tertiary datum feature as the third axis of the part coordinate system is derived from the primary and secondary datum setup steps using this method.

The second method to handle part alignment is specified to affect the already defined coordinate systems through a sequence of translation or rotation steps. The translation and rotation actions are defined by a value or by aligning to other features. The sign of the value defines on which axis direction the affected origin will be translate

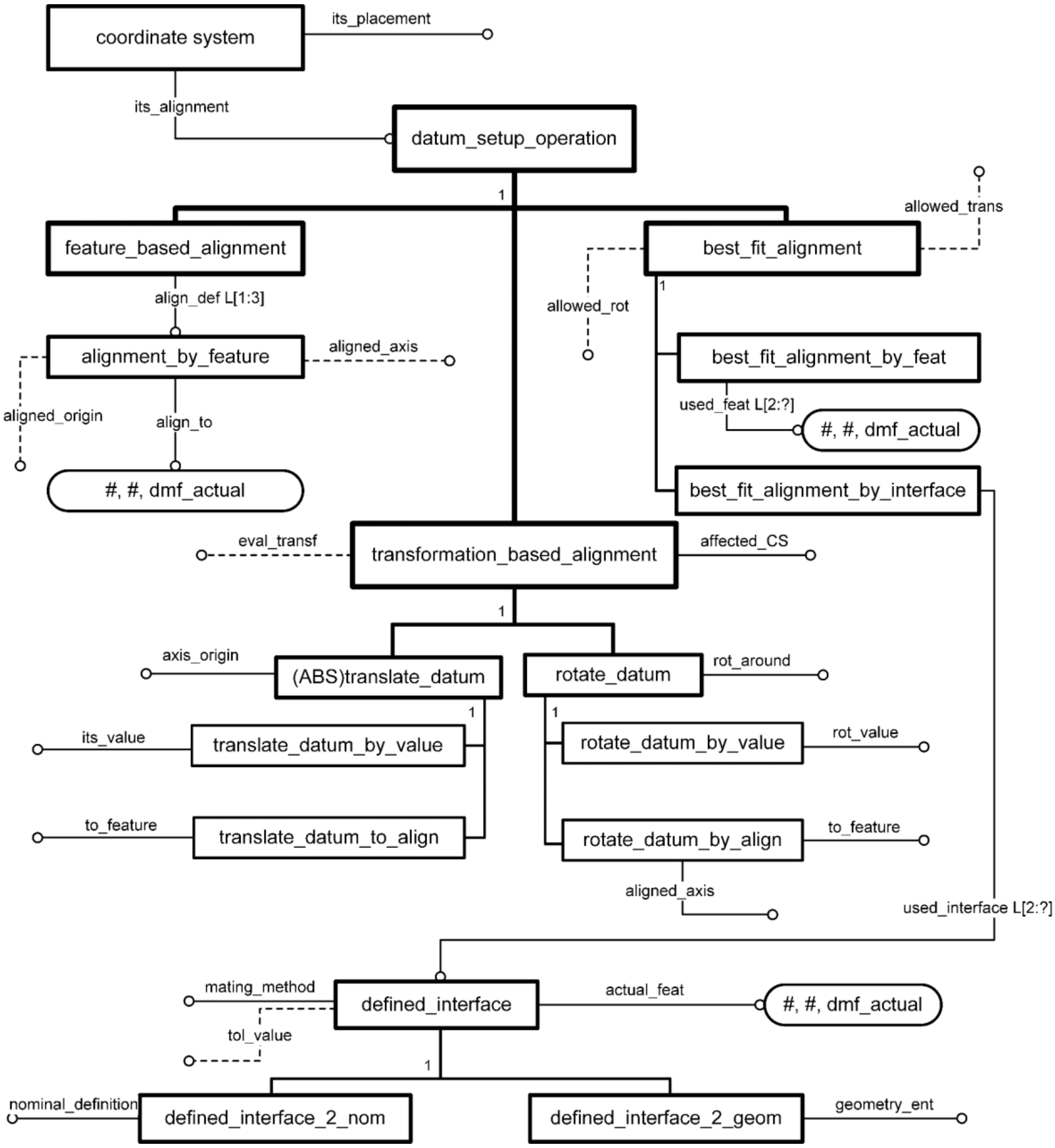


Figure 6-44: REIMS part alignment operation

or axis to rotate. In Figure 6-44, REIMS specifies `translate_datum` and `rotate_datum` entities to represent these alignment methods. These entities are subtypes of `transformation_based_alignment` entity that references an already defined part coordinate system. In a `translate_datum` step, information about which origin will be translated and with what value or to what feature is necessary. In a `rotate_datum` step, the rotation axis and the rotation value are specified. The rotation value could be derived by aligning an axis of the coordinate system to a specified feature.

The third method is used when datum axes are not related directly to specific features to be aligned with them. In such cases, actual feature data, either measured or constructed, is used to align the part by fitting the data to their related nominal feature definitions or CAD geometries. The measurement planner could control the fitting results to respect a specified preferable direction of fitting by limiting the allowed directions of the translation or rotation of fitted geometry. REIMS defines the `best_fit_alignment` entity to represent this kind of complex alignment processes. Optional attributes are defined to allow specific control on the fitting directions. As shown in Figure 6-44, `best_fit_alignment_by_feature` is a subtype that uses actual features and their nominal definitions to calculate part coordinate system through a fitting process. In addition, the `best_fit_alignment_by_interface` entity uses defined interfaces to evaluate part coordinate system through the fitting process. A `defined_interface` entity couples a nominal definition to an actual definition with a specific preferred direction for fit. The nominal definition does not need to be related to the actual data, as it can be the nominal definition of datum targets used for locating complex parts.

6.3.7. Evaluation operation

Evaluation means to assess whether an actual feature complies with tolerance limits or zone defined by design specifications. The REMIS data model specifies three different entities for representing different evaluation mechanisms to map different methods used in measurement practice during the final evaluation step. These entities are defined as subtypes of `evaluation_operation` abstract supertype entity as shown in Figure 6-45. The `manual_evaluation_operation` entity is defined to represent the evaluation of specification using manual devices such as gauges or linear measurement instruments while the other two subtypes are used to represent evaluation operations done through the analysis of the coordinate measurement data. The `soft_gauging_operation` entity provides the necessary data for simulating the gauging process numerically, and the `coordinate_evaluation_operation` entity is used to represent the conformance assessment in coordinate metrology systems by analysing feature data to match standardised specification definitions.

Extracted feature data is analysed according to the specifications applied to these features. For example, actual linear or angular dimensional characteristic evaluation only requires the construction of representative reference elements of actual entities included in the characteristic definition. Reference elements are `dmf_associated` features, as shown in Figure 6-46, whose construction operation is defined based on the

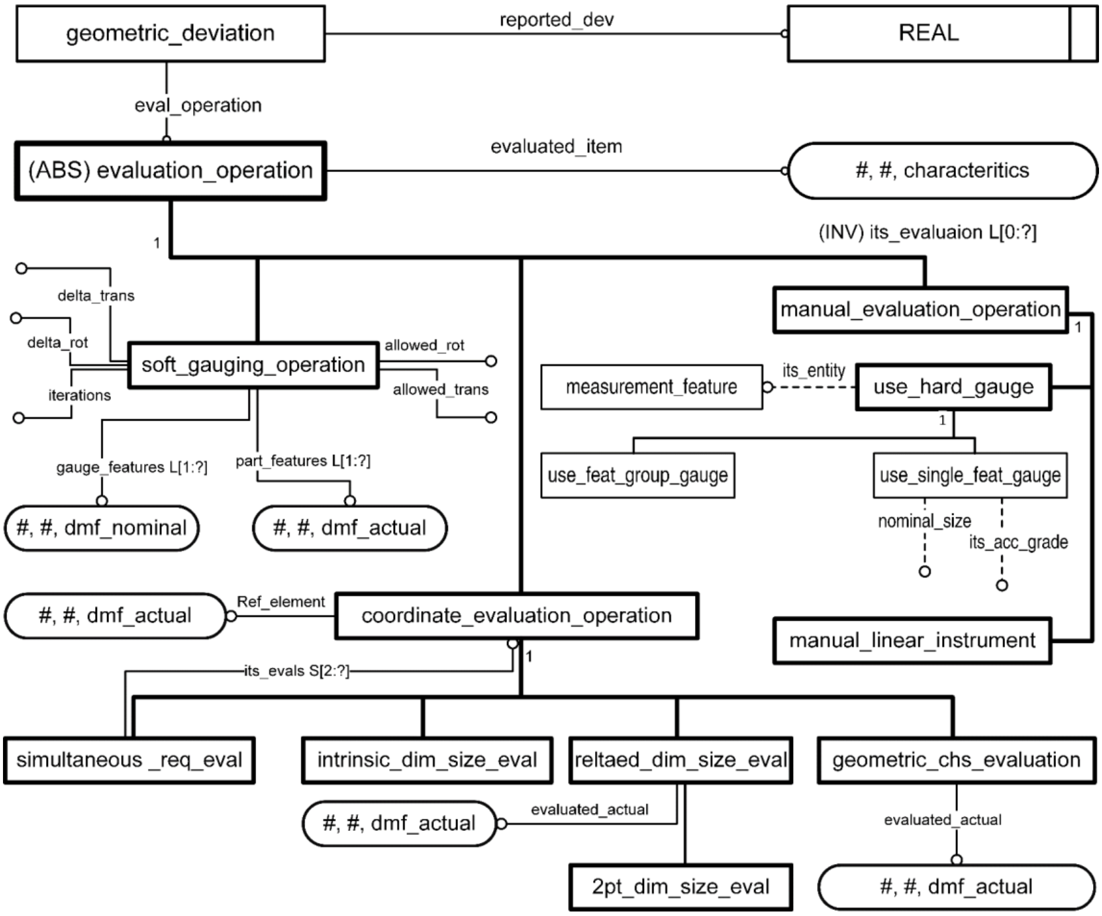


Figure 6-45: REIMS measurement evaluation operation

characteristic and feature definitions. The distance or angle calculated between references elements are then compared to the tolerance data provided by the evaluated characteristic. On the other hand, evaluation of geometric deviations is based on the normal distance between the actual feature and its related reference element, as shown in Figure 6-46. This normal distance is then compared to the tolerance zone size defined

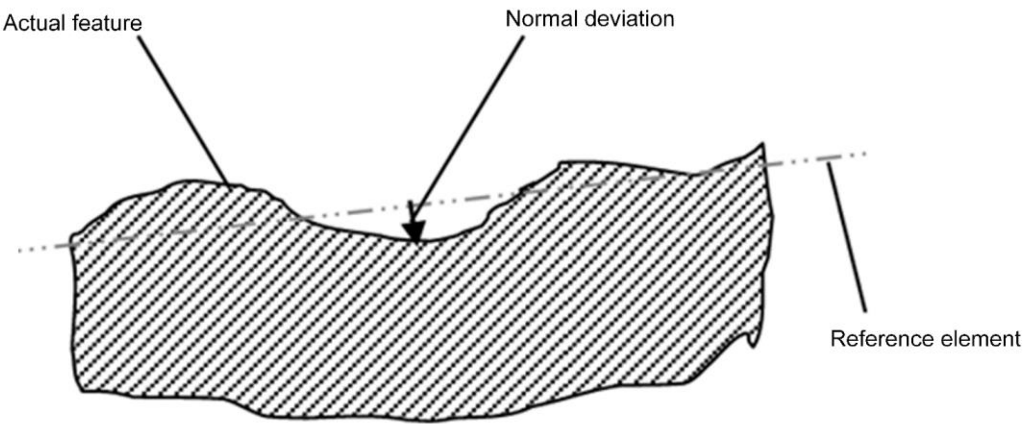


Figure 6-46: Geometric deviation evaluation concept

by geometric characteristics. Actual features in geometric deviation evaluation are either dmf_extracted or dmf_filtered actual features. Each evaluation operation should report an evaluated parameter that can be a distance in linear dimensional, form, orientation, location and run-out characteristics or an angle in angular dimensional characteristics. Surface texture has its own distance parameters that need to be specified for the evaluation operation including a reference to peak, a reference to valley, a peak to valley and the root mean square values; the required parameters for evaluation are determined using specification modifiers defined in ISO 1101/Amd1 (ISO 2012a).

In Figure 6-45, the coordinate_evaluation_operation entity has different subtypes to accommodate various evaluation scenarios. This entity references a dmf_actual entity as an attribute that represents one entity involved in the evaluation process. Some evaluation processes require only dmf_associated elements to report intrinsic direct global size as defined in ISO/DIS 14405 (ISO 2013c). REMIS represents direct global size evaluation by defining the intrinsic_dim_size_eval entity. Conversely, the related_dim_size_eval is specified in REIMS to represent those evaluation operations requiring two dmf_actual features. In fact, these two actual features are of type dmf_associated unless the derived 2pt_dim_size_eval entity is used, in which case actual features are of type dmf_extracted and they are in fact points. This derived entity is defined to accommodate local size evaluation as defined in ISO/DIS 14405 (ISO 2013c). The 2pt_dim_size_eval entity is that entity requires relaxation of the dmf_associated features to dmf_actual features referenced with coordinate_evaluation_operation entity and its subtypes.

The geometric_chs_eval entity is defined to represent the evaluation of geometric characteristics that requires two dmf_actual entities. One of them is dmf_associated reference feature as shown in Figure 6-46. The simultaneous_req_eval entity is defined to represent cases where there are different characteristics that need to be evaluated simultaneously. Figure 6-47 shows an example of one case that requires a simultaneous evaluation of profile and position characteristics as they reference the same datum reference frame with same datum precedence and datum boundary modifiers. In Figure 6-45, the soft_gauging_operation entity represents the data required by a measurement software to simulate gauging operation numerically and check for interference between a constructed gauge and evaluated part data. This entity requires the list of actual part features and their related gauging feature. The gauging features are nominal feature

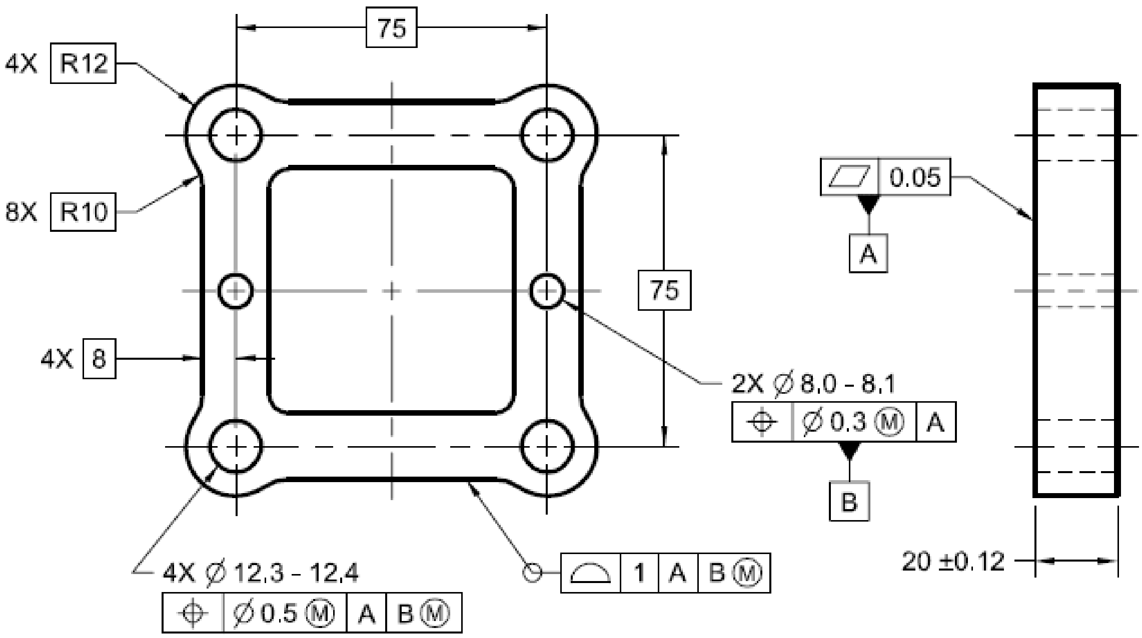


Figure 6-47: Example of simultaneous verification requirements (ASME 2009)

definitions of simulated gauge that are modified according to any applied material modifier to the tolerance value. The other attributes of `soft_gauging_operation` define the direction and axes along which the simulated gauge could translate along or rotate about according to the invariance class of the related datum system and the minimum translation and rotation value per each iteration. The entity also defines the maximum number of testing iterations before reporting that there is interference between the soft gauge and actual part data. It should be noted that Figure 6-45 presents an inverse relation from a characteristic to its evaluation operation; the cardinalities of this relation is set to zero-to-many, as general default characteristics may not require evaluation steps and a single characteristic may be evaluated the same number as its nominal entity was extracted.

6.4. Design characteristics

Design characteristics are included in MBD to form the input from the design stage to measurement stage as discussed in section 3.1. Characteristics can be classified into two distinct types that are dimensional and geometrical characteristics. These characteristics are specified to define acceptable limits within which real part surfaces and parameters can vary. From the measurement planning perspective, getting a characteristic and being able to obtain its related nominal measurement feature(s) is considered necessary to guide the statement of measurement operation definitions.

Figure 6-48 shows the `characteristic` abstract top-level entity in REIMS. In the figure, the `characteristic` entity has `geometric_characteristic` and `dimensional_characteristic` as its subtypes to represent the two different types of characteristics. The `default_characteristic` entity is used to hold those general specifications for parameters and features with no specification in MBD; hence, this entity references the definition of the `characteristic` top-level entity.

The `characteristic` entity references `is_freestate` and `its_status` Boolean attributes. The free-state Boolean attribute, if evaluated to true declares that the attributed characteristic is to be evaluated in a free state. The Boolean attribute `its_status` defines if the attributed characteristic is already checked or evaluated or not yet in the measurement environment. The `key_characteristic` entity assigns a criticality designation with a unique label to a specific characteristic. According to ISO 22093 (ISO 2010c), the criticality designation can be *minor*, *major* or *critical*. REIMS representation of both dimensional and geometrical characteristics assumes that design stage is responsible for validation of the correctness and completeness of published specifications to the measurement phase. The REIMS data model is enumerated by information by querying CAD database for different information.

6.4.1. Dimensional characteristics

Specification standards such as ISO 1101 (ISO 2012b), and ASME Y14.5 (ASME 2009) classify characteristics into geometric and dimensional characteristics. REIMS

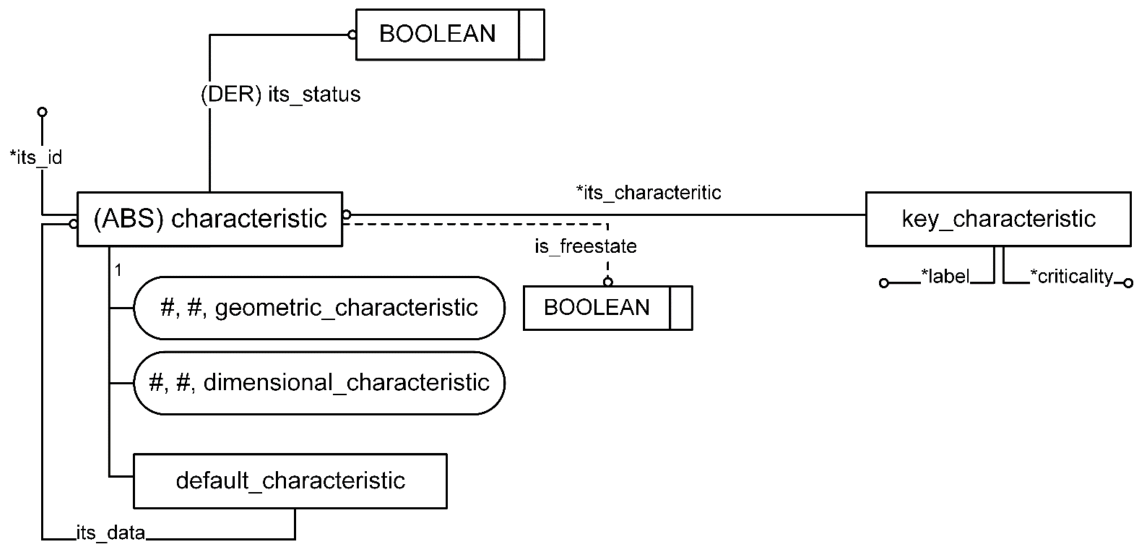


Figure 6-48: REIMS characteristic abstract supertype entity

maps this classification by introducing the geometric_characteristic and dimension_characteristic entities. The dimension_characteristic supertype entity is defined to link dimension type, dimensioned elements and dimensional specification as shown in Figure 6-49. This entity references a dimensional_tolerance entity as an attribute if the dimension_characteristic entity is not representing a basic or reference dimension. Basic dimensions are not intended to be measured or evaluated but are used by construction operations during the positioning of reference elements of tolerance zones with respect to datum systems The dimensional_tolerance entity specifies upper and lower limits of the nominal_value attribute of the dimension_characteristic entity.

A dimension_characteristic entity can be an intrinsic or a situation characteristic according to ISO 25378 (ISO 2011j). For example, the size parameter of a FoS is an intrinsic characteristic while situation characteristic relates two entities that are both measurement features or a measurement and a datum features for positioning purposes. In Figure 6-49, the intrinsic_characteristic and situation_characteristic entities are defined as subtypes of dimension_characteristic entity for representing these two types of dimensions. In addition, the dimension_characteristic entity can represent a directed dimension if its is_directed Boolean attribute evaluates to true; directed dimension requires a directed measurement as shown in Figure 6-50. In this case, the measurement operations should consider the direction as being from the reference_element to first_element attributes representing the dimensioned measurement elements. In fact, the reference_element attribute is optional as a dimension_characteristic entity can only refer to one measurement feature as in the case of a diameter of a cylindrical feature. The value_modifier attribute is defined to hold any linear or angular dimension modifiers as defined in ISO 14405 (ISO 2013c). Table 6-4 shows, as an example, the linear dimension modifiers that are used to describe further the applied dimensions as being local or global characteristics that are as described in subsection 4.2.3.

In Figure 6-49, different subtypes are included in the REIMS data model to represent different intrinsic and situation dimension types exist within specification environment. REIMS defines these subtypes based on the characteristic definitions introduced in ISO 25378 (ISO 2011j). The situation characteristics can be either linear or angular dimensions. The subtypes of linear_locational_dim and

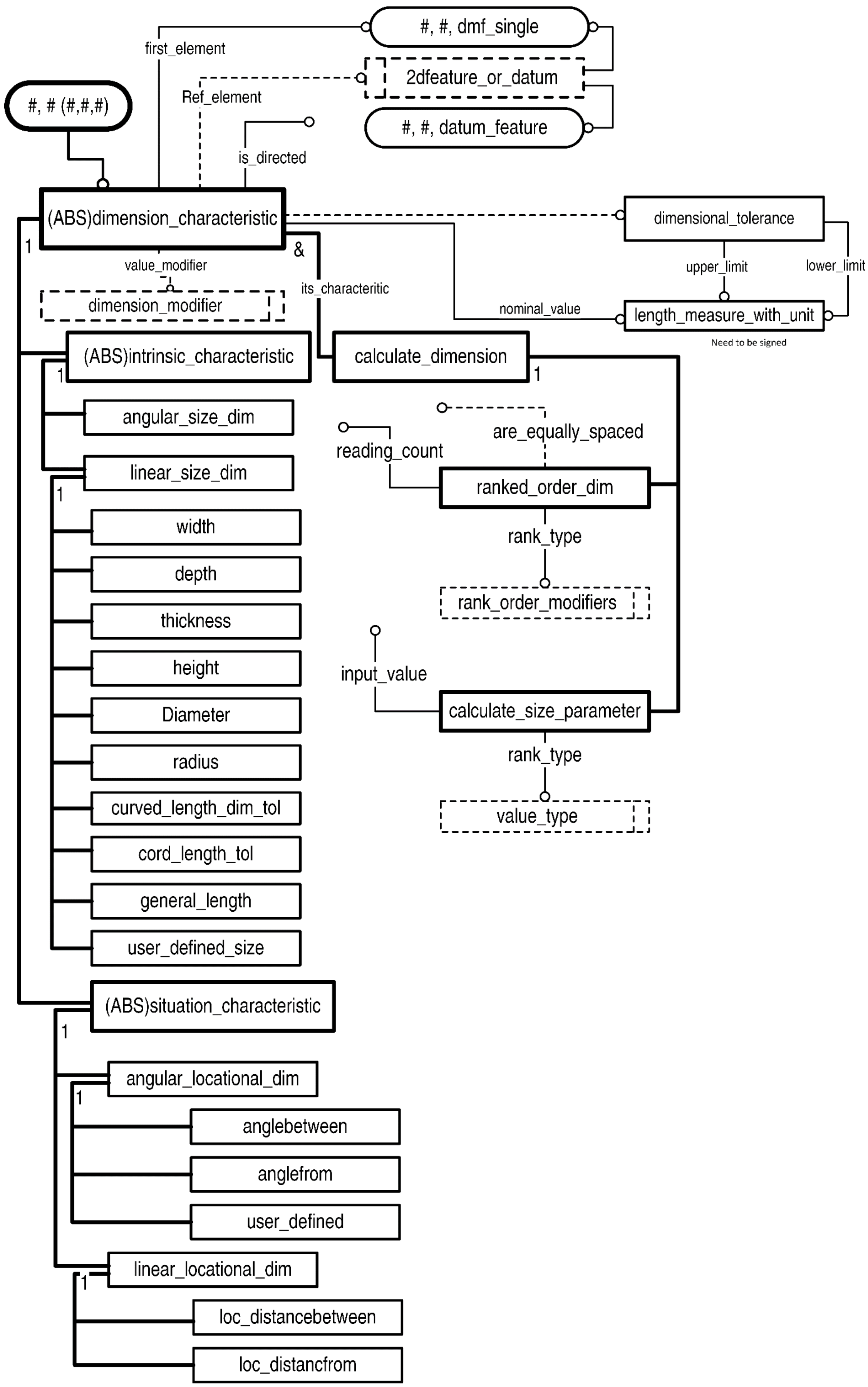


Figure 6-49: REIMS dimensional characteristics and tolerances

(a) (b) (c)

Figure 6-50: Examples for directed measurement indication (ASME 2009)

`angular_locational_dim` are defined to determine location dimensions between two entities or from a datum to an entity. The subtypes of the `intrinsic_characteristic` entity are defined to represent different linear and angular size types such as width, depth, thickness and height.

As illustrated in Figure 6-49, intrinsic or situation characteristics can form more complex entities via the AND inheritance relationship with `calculated_dimension`

Table 6-4: Specification modifiers for linear sizes (ISO 2013c)

Modifier	Description
(LP)	Two-point size
(LS)	Local size defined by a sphere
(LL)	Local least outer material size
(GG)	Least-squares association criterion
(GX)	Maximum inscribed association criterion
(GN)	Minimum circumscribed association criterion
(GC)	Minmax association criteria[a]
(CC)	Circumference diameter (calculated size)
(CA)	Area diameter (calculated size)
(CV)	Volume diameter (calculated size)
(SX)	Maximum size[a]
(SN)	Minimum size[a]
(SA)	Average size[a]
(SM)	Median size[a]
(SD)	Mid-range size[a]
(SR)	Range of sizes[a]
(SQ)	Quadratic range of sizes

[a] Rank-order size can be used as a supplement to calculated portion size or global portion size or local size (see 3.11.2.2 and 6.2).

entity presented in ISO 25378 (ISO 2011j). The calculated_dimension entity has two subtypes: the ranked_order_dim and the calculated_size_parameter entities. The ranked_order_dim entity is defined in ISO GPS as a global characteristic that is evaluated based on a rank_order_modifier and over a number of readings that can be optionally specified as being equally spaced. Given a number of measurement parameter readings, the ranked_order_dim entity can be used to report different values based on the value of rank_order_modifier entity; examples include maximum, minimum, average, median, mid-range and range of a set of input parameter values. The representation of the ranked global characteristic is necessary to accommodate situations such as when it is required to report the average diameter of a feature on a flexible part with a free-state modifier that requires the measurement of the diameter at many inspection locations then reporting the ranked diameter, average and value. On the other hand, the calculated size is used to report the diameter of a feature given either its circumference, area or volume value. REIMS specifies a calculated_size_parameter entity, as shown in Figure 6-49, to represent this type of calculations based on a specified value_type attribute.

6.4.2. Geometric characteristics

The geometric characteristics, the second type of characteristics, are defined to specify limits within which nominal geometries defined in CAD database are allowed to vary. REIMS defines geometric_characteristic abstract supertype entity to represent geometric characteristics as shown in Figure 6-51. According to ISO 1101 (ISO 2012b), and ASME Y14.5 (ASME 2009), a geometric characteristic defined a tolerance zone with respect to which the toleranced feature is evaluated. REIMS used this definition to represent the necessary attribute to completely define a geometric characteristic.

The geometric_characteristic entity is related to the measurement_feature it specifies as one of its attributes. In addition, the geometric_characteristic entity has a geom_tolerance_zone entity as an attribute whose size is represented by the geom_tol_value entity attribute. Finally, a geometric_characteristic entity allows its geom_tolerance_zone attribute to be optionally defined with respect to a datum_system entity, as the case requires for example in location and orientation geometric tolerancing where the tolerance zone is locked in position and/or orientation.

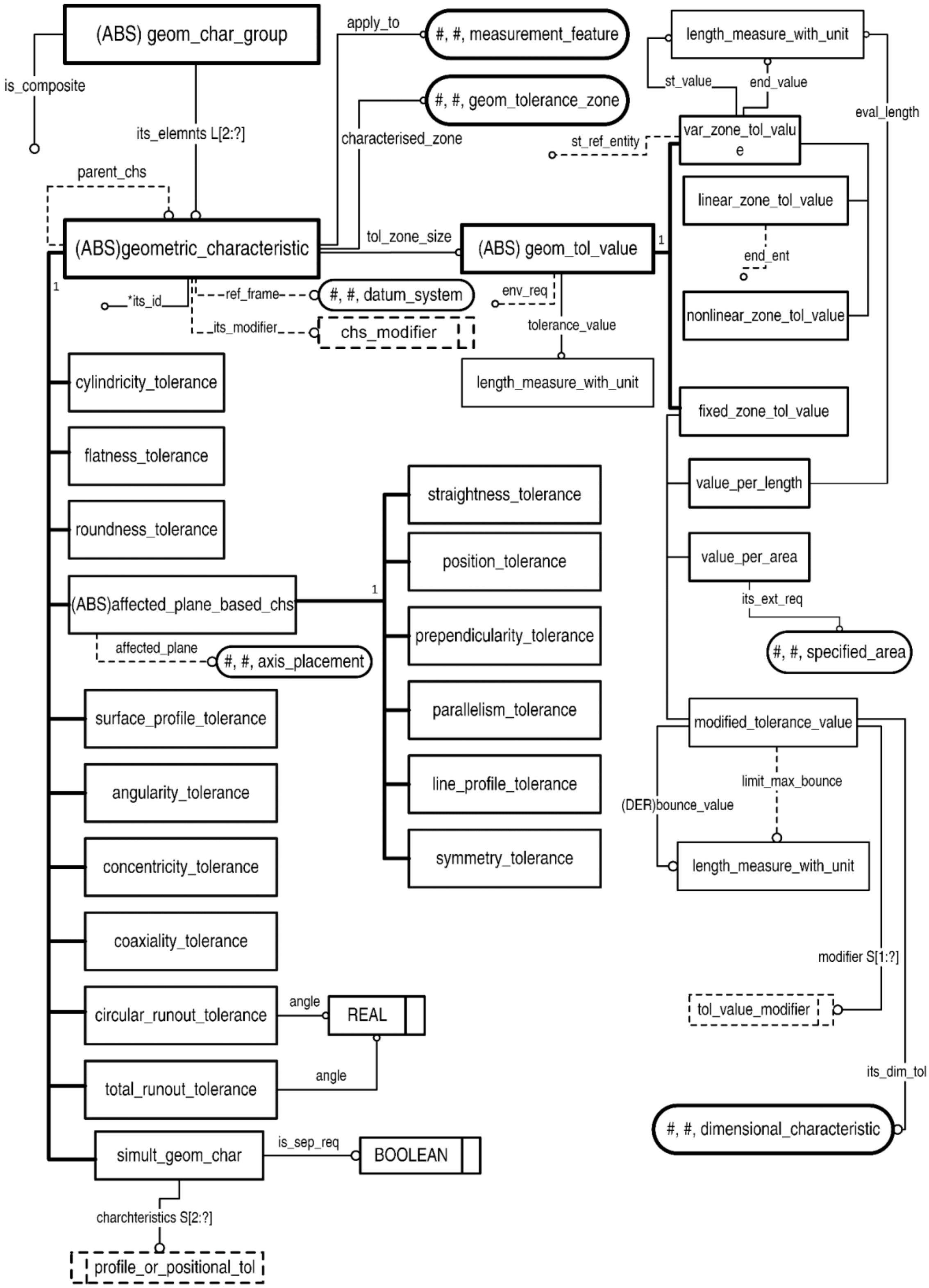


Figure 6-51: REIMS geometric characteristic

In Figure 6-51, the `geom_tol_value` entity represents the tolerance zone size through its `tolerance_value` attribute. The `geom_tol_value` entity has `envelop_req` Boolean attribute to indicate that the satisfying envelope boundary is required by the toleranced feature. Envelope requirement is dependent on the checking of both the local size and the global virtual condition of a FoS and is specified using (E) modifier in ISO 1101 (ISO 2012b), however, it is the default case in ASME Y14.5 (ASME 2009). Furthermore, ISO1101 (ISO 2012b), defines tolerance zone size as being fixed along the toleranced feature or as being varied linearly or nonlinearly between two limit values at starting and ending geometric entities. In the REIMS model, the `geom_tol_value` entity has `var_zone_tol_value` and `fixed_zone_tol_value` entities as subtypes to represent the different specifications of the tolerance zone size. The `var_zone_tol_value` entity defines two subtypes for linear and nonlinear variable tolerance zone. On the other hand, `fixed_zone_tol_value` entity defines `value_per_length`, `value_per_area` and `modified_tolerance_value` as its subtypes. These subtypes represent tolerance zones that are specified for a specific length or area on a feature or specified with a material modifier that modifies tolerance zone size for FoS. The defined tolerance-per-length limits the extent of the measurement extraction operation to the value of `eval_length` attribute. The defined tolerance per restricts the feature extent to which tolerance applies and hence requires the `specified_area` enabling entity as shown in Figure 6-18.

The `modified_tolerance_value` subtype entity defines a tolerance zone size that is modified by a material modifier. Material modifiers provide a bonus that can be used by a geometric entity related to a FoS when a linked dimensional characteristics deviated from its upper or lower tolerance limits. The use of bounce value can also be limited by the MAX modifier. Bounce tolerance is based on the material modifier type and the evaluated actual value of a dimensional characteristic of FoS related to the geometric characteristic under consideration. Material modifiers can be used with FoS with a dimensional characteristic specified on its size parameter in addition to locational, form or orientation geometric characteristics that are applied to the situation derived feature of the FoS. REIMS represents this situation through linking of the modified geometric tolerance value to the defined dimensional characteristic specifying the parent integral element(s) of a FoS. The modified tolerance zone size is commonly checked through gauging principles in measurement practise using either hard-gauging or soft-gauging methods.

Figure 6-51 shows the geometric_characteristic entity and its various subtypes. Among these subtypes, there are characteristics that are view-dependent, as shown in Figure 6-15. This means their interpretation for extraction or evaluation operations depends on the view in the drawing on which they are indicated. The affected_plane_based_tolerance entity is defined to gather the view-dependent characteristics such as straightness and line profile tolerances where the specification of extraction direction is affected by the affected_plane attribute. In addition, the perpendicularity, parallelism and position tolerances used the affected_plane attribute to determine the direction of non-cylindrical tolerance zones.

The simult_geom_char subtype entity is defined to represent simultaneous verification requirements of two or more geometric tolerances that apply as a single requirement for a pattern or a part. Simultaneous requirements apply, by default, for any combination of position and profile tolerances that are located by basic dimensions with respect to the same datum features that are referenced in the same order of precedence at the same boundary conditions (ASME 2009). If the simultaneous requirement - as a default requirement - is not necessary in a specific case, this should be made explicit using the is_sep_req Boolean attribute.

REIMS defines the geom_char_group entity to represent composite and two-single-segment characteristics that may be found within design specifications. Figure 6-52 shows the difference between composite and two-single-segment tolerance groups as defined in ASME Y14.5 (ASME 2009). The geom_char_group entity consists of a unique list of geometric_characteristic entities that forms the composite or two-single-segment characteristics. Each characteristic entity within the group is evaluated independently. Composite tolerancing represents composite tolerance frames that are specified for a pattern of features; patterns may require a larger tolerance relative to the datum system while a tighter one within the features forming the pattern. Each characteristic except the first one in the group references its preceding segment through the its_parent attribute. If this attribute is not specified, this means that this is the first segment in the group called a pattern-locating tolerance zone framework (PLTZF). According to ASME Y14.5 (ASME 2009), a PLTZF should define the extraction operation while the other lower segments can use the extracted data for their analysis for not repeating the extraction operation definition for the same feature. It should be noted that the related reference elements of the tolerance zones of the PLTZF segment are constructed with relation to the defined datum system as this segment controls both

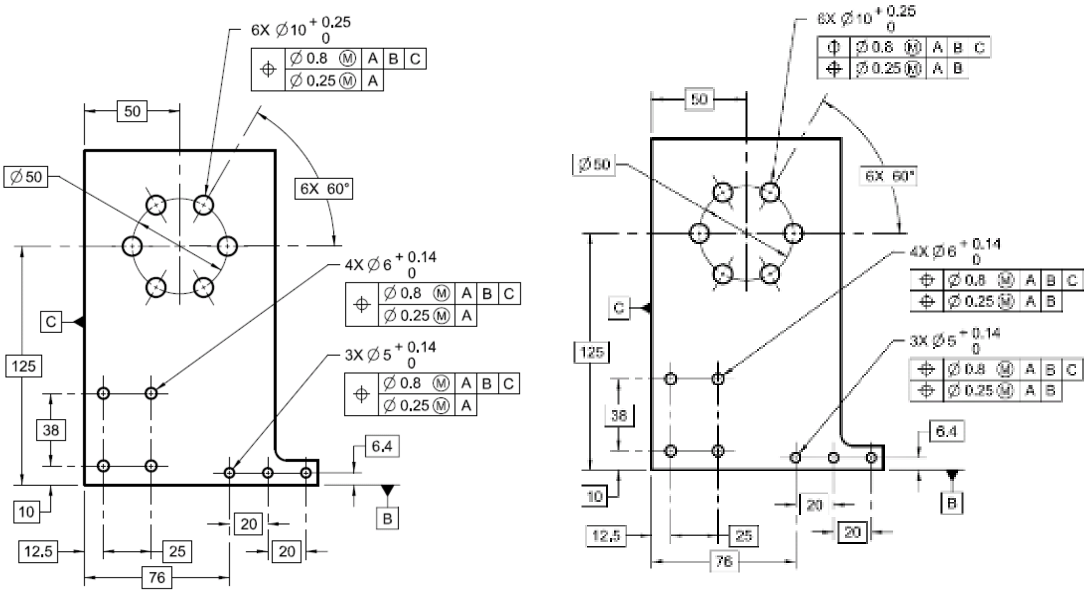


Figure 6-52: Composite and two-single segment specification indications (ASME 2009)

location and orientation of the pattern's elements. Other lower segments are called feature-relating tolerance zone framework (FRTZF) according to ASME (2009) and they control orientation only of the pattern's elements; hence, these zones are not affected by the basic dimensions relating them to datum features. On the other hand, multi-segment tolerance is neither specific for a pattern or inter-features relations, but both are considered together. In a multi-segment tolerance group, basic dimensions relative to datum systems applies for all segments.

6.4.3. Datum systems

Datum reference frame consists of one or more datums to establish relationships imposed by geometric tolerances and for constraining part degrees of freedom (ISO 2012b; ASME 2009). REIMS defines `datum_system` entity to represent datum reference frames as shown in Figure 6-53. The REIMS model assumes that checking of rules to control a maximum number of datums for specific characteristic types is performed by the CAD system before exporting the CAD file. The `datum_system` entity is related to a part coordinate system that is represented by `its_placement` optional attribute. The `datum_system` entity references a unique list of a maximum of three `datum` entities to represent those datums in the tolerance control frame forming the datum system. A datum can be based on features or targets; REIMS used three different subtypes for the `datum` entity to represent different datum natures. Each datum entity can be modified with variable modifiers to qualify datum simulator size or to modify the restricted DoF(s) by this datum as shown in Table 6-5. The datum precedence is derived

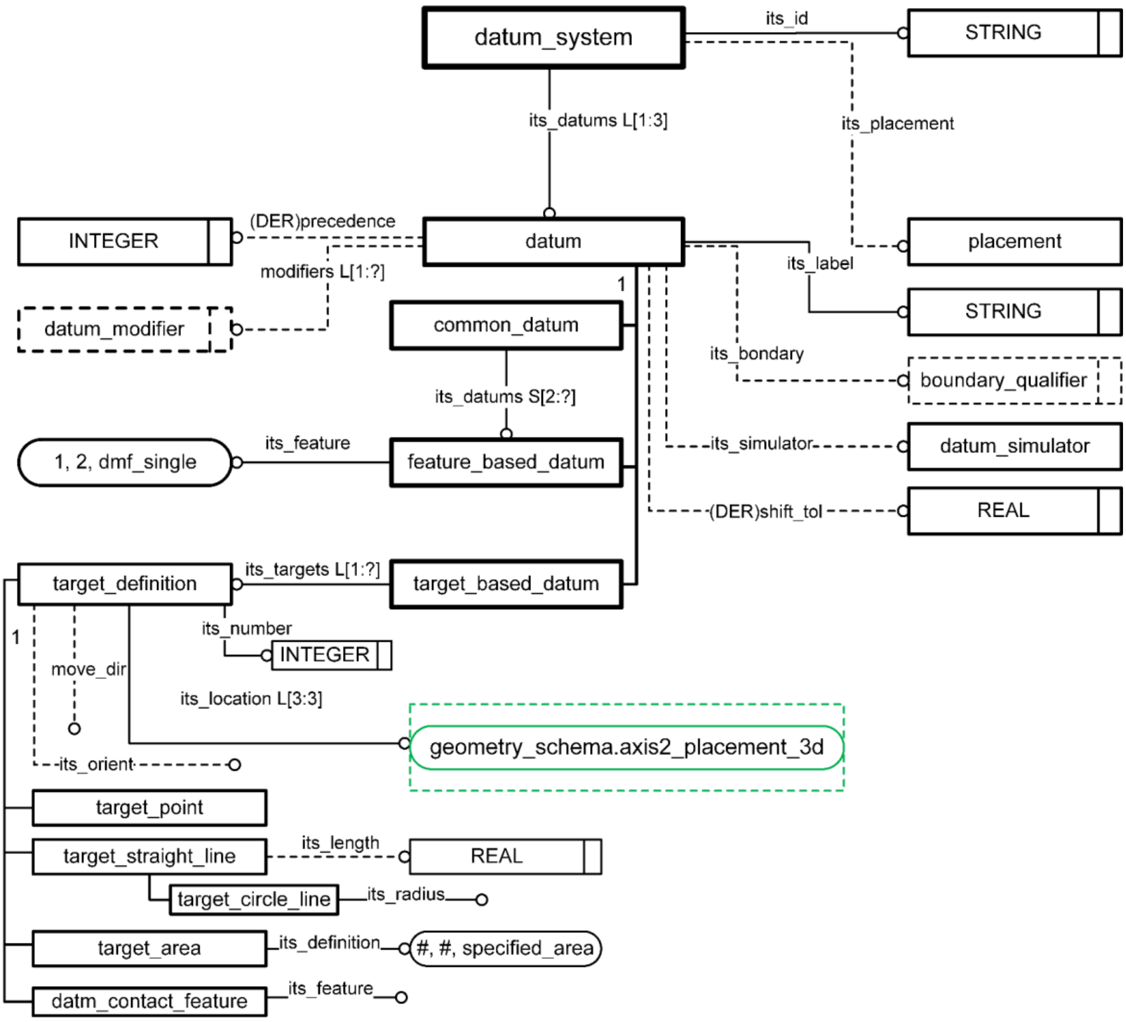


Figure 6-53: REIMS datums and datum systems

from the datum position in the list referenced by the `datum_system` entity and can be recorded explicitly in the optional, derived precedence attribute.

A datum locks all DoFs of the tolerance zone that are required by the geometric characteristics type and have not been already locked by the preceding datums. Each datum can lock specific DoF(s) based on its shape and invariant degree of freedom class. A datum can be modified by the orientation-only modifier to unlock the location constraints that can be imposed by a datum on a tolerance zone by a datum. More flexibility is provided for the designer to control how the datum locks tolerance zone by relaxing the datum feature and treating it as a more simplified situation feature using the situation modifiers in Table 6-5. Each datum among those forming the datum system can be any of; `feature_based_datum`, `target_based_datum` or `common_datum` entities.

Table 6-5: Datum boundary qualifiers and datum modifiers

Modifier	meaning
M	Maximum material boundary
L	Least material Boundary
P	Projected (for secondary and tertiary datum)
DV	Distance Variable (for common datums)
CF	Contacting Feature (datum targets)
PL	Situation feature of type (plane)
ST	Situation feature of type (straight line)
PT	Situation feature of type (point)
><	Apply orientation constraints only

The `feature_based_datum` represents those datums that are based on datum features of type `dmf_single` entity. The `common_datum` entity represents those datums established from two or more `feature_based_datum`(s) that are considered simultaneously to establish a single datum in a datum system. The `target_based_datum` is used to represent those datums established using datum targets represented by `target_definition` entity. Datum targets are used with complex or irregular surfaces to form datums or generally when the entire surface feature is not suitable for establishing a datum. Contacting target elements define a specific interface to which the corresponding features need to mate. The target element can be a point, a line or an area. A point target is defined by its location while the line target is defined by its placement in 3D and, optionally, its length. A datum target line can take a circular shape, in which case, the radius of the circle is required. The target area can be defined by referencing the `specified_area` entity defined in Figure 6-18. A target can be specified to be movable with a translation modifier in a non-default direction, which is perpendicular to the part surface, in which case, the optional `move_dir` attribute is used to represent the specified movement direction.

ISO 5459 (ISO 2011a) recommends a number of rules for the association operation for different datum types. Datums are specified to be constrained to be outside the part and with one of the following association methods: minimum inscribed, maximum circumscribed and minimize maximum distance association methods. It is also specified for common datum, for which, associated features are constrained by default in both location and orientation to each other. This default behaviour can be modified by the distance variable modifier, shown in Table 6-5, which allows the linear dimensions of the collection to be variable.

For datum targets, it should be noted that, in some cases, the associated feature establishing the datum is not of the same type as the nominal feature. In such a case, the datum is modified by the contact feature (CF) modifier as shown in Table 6-5. The interface to which the non-ideal feature is associated is determined by the shape and dimensions of contacting target elements. Other rules for intrinsic parameters during association are stated, e.g. for a single datum feature; the intrinsic parameter is variable by default except for cone and wedge whose angle is considered fixed during associations. In addition, in common datums, each datum is treated as for a single datum, but the intrinsic dimension of collection is considered fixed during the association but may be modified by variable distance modifiers shown in Table 6-5. When considering datum precedence in a datum system, each datum is treated as a single datum for relations between datums. Linear dimensions are considered variable while angular dimensions are considered fixed during associations. Such rules are helpful for defining construction operations required for establishing the datums and datum systems during the measurement process.

6.4.4. Tolerance zones

Geometrical tolerances, when applied to features, define tolerance zones within which features shall be contained. According to ISO 1101 (ISO 2012b), tolerance zone is space limited by one or several geometrically perfect lines or surfaces and is characterised by a linear tolerance dimension. Tolerance zone is defined by its shape, placement, if constrained, and extent. REIMS defines the `geom_tolerance_zone` entity to represent tolerance zones defined by geometric characteristics and constrained by datums if they are of a related type as shown in Figure 6-54.

Tolerance zone shape is dependent on the characteristic type and the toleranced feature type and can take many shapes such as ‘cylindrical’, ‘parallelepiped’, ‘spherical’, ‘profile’ and ‘two parallel lines’; this is represented by the `zone_shape` entity. Tolerance zone placement is defined based on the nominal shapes of datums in related datum system if they exist and the characteristic type. By default, tolerance zone is positioned symmetrically from the constructed reference elements of measurement features unless this is modified by unequal zone modifier (UZ). The UZ modifier indicates that the location of the tolerance zone is offset by a specific value that can be positive or negative.

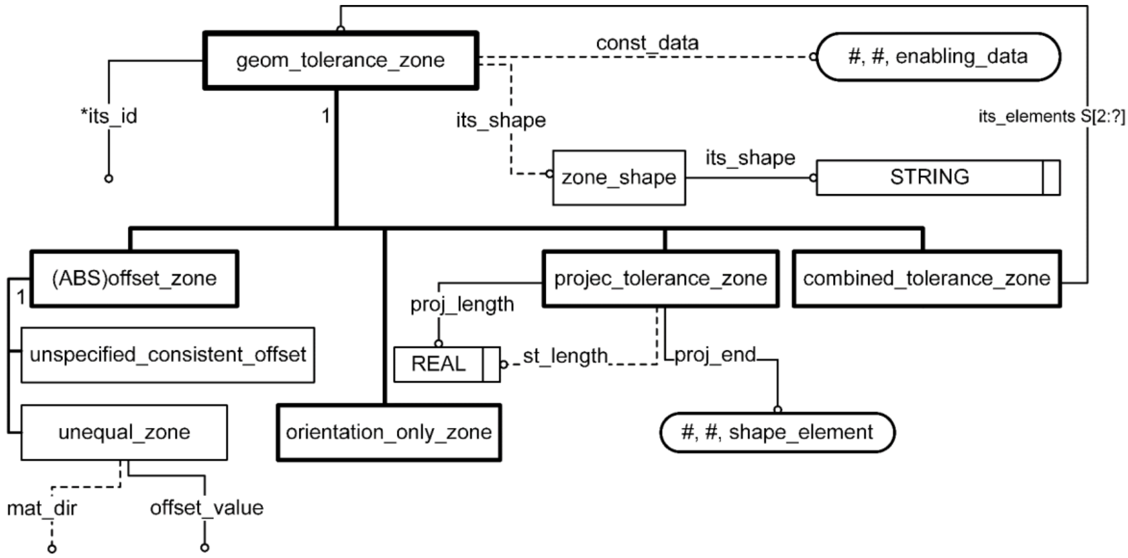


Figure 6-54: REIMS tolerance zone entity

This would allow the offset to be on the outside or inside with respect to the material direction.

The offset zone (OZ) modifier, on the other hand, indicates an offset tolerance zone with consistent but unspecified value. The material direction may need to be specified explicitly, for example, when a sheet metal part is modelled without thickness information. The default and offset positioning of a tolerance zone are as shown in Figure 6-55. REIMS defines the `offset_zone` entity and its subtypes to represent tolerance zones modified by UZ and OZ modifiers. The width of the tolerance zone is specified by

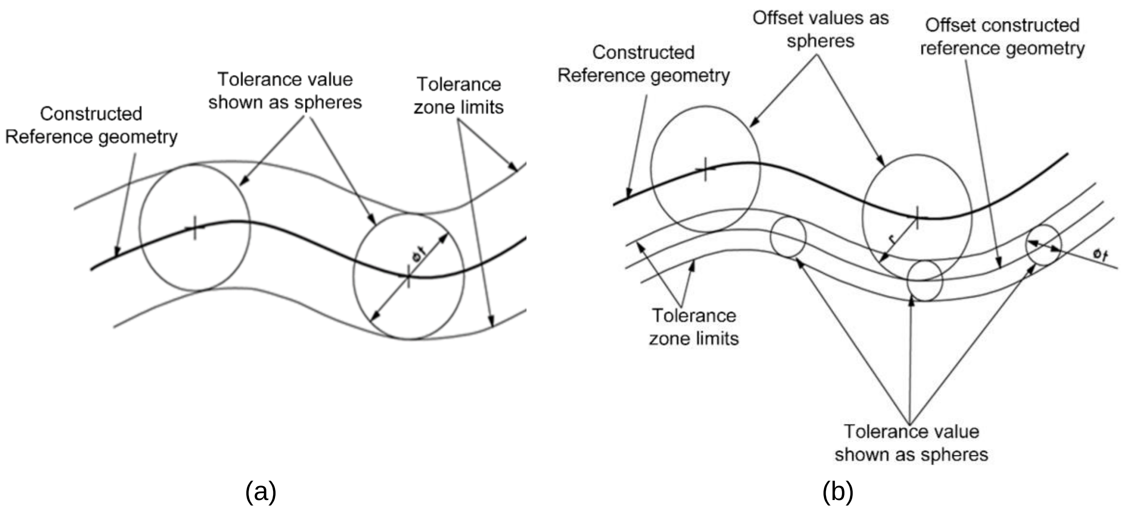


Figure 6-55: Default and offset positioning of tolerance zone; Modified from ISO/DIS 1660 (ISO 2013b)

the tolerance value and can be a single fixed value or variable between two limit values as shown in Figure 6-51. The tolerance zone width, by default, applies normal to the specified geometry, but for roundness specifications, it applies in the intersection plane perpendicular to the associated axis of the specified surface. In non-default situations, the definition of a direction feature that is a feature from which the direction of the width of the tolerance zone is determined becomes necessary as defined in ISO 1101 (ISO 2012b). Figure 6-56 shows how a direction vector is presented in 3D MBD and how it affects the direction of the width of the tolerance zone.

In addition, the orientation of the tolerance zone is necessary if the tolerance zone is non-diametrical and is applied to a derived feature; In this case, the tolerance zone interpretation is view dependent. The orientation plane is defined when it is necessary to explicitly define tolerance zone orientation. Both the direction feature and the orientation plane data, if specified to modify or specify the tolerance zone are represented in REIMS through the `enabling_data` attribute referenced by the `geom_tolerance_zone` entity; the `enabling_data` is represented as shown in Figure 6-12.

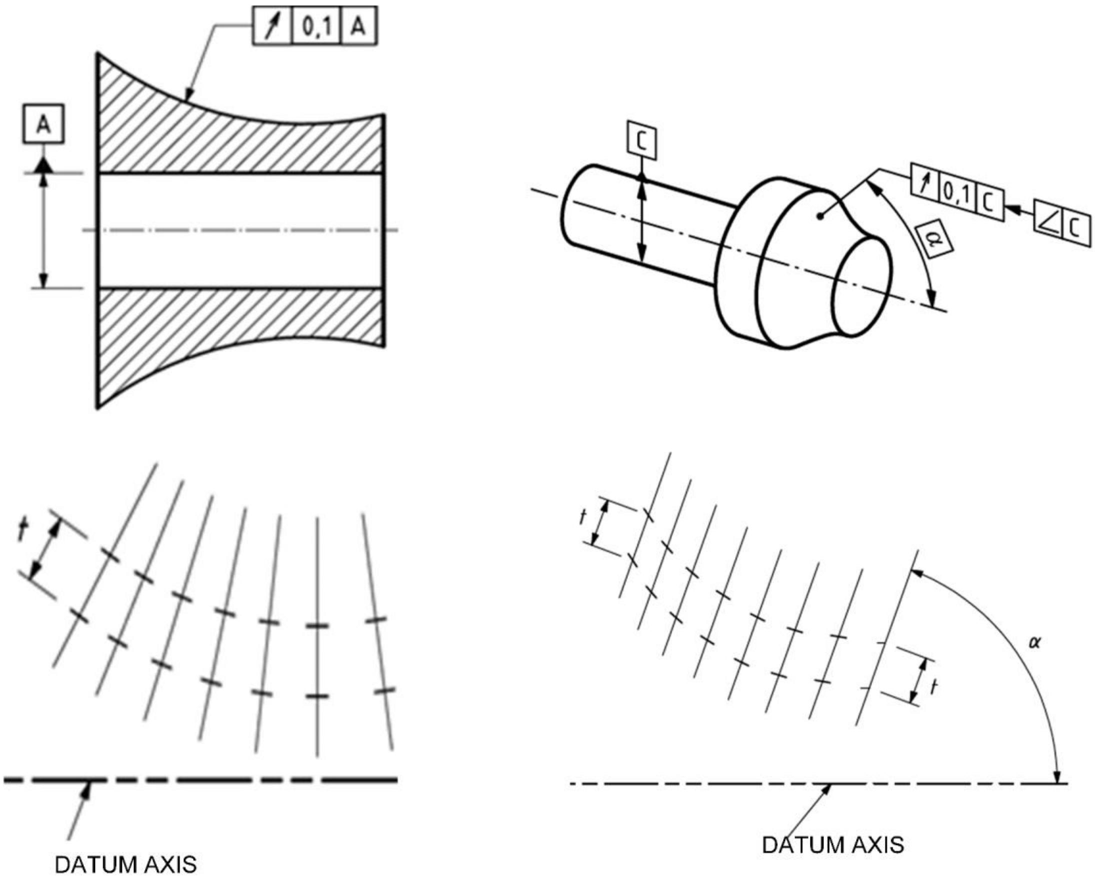


Figure 6-56: Effect of direction feature on the tolerance zone width direction; Modified from (ISO 2012b)

Profile tolerances apply, by default, to one feature in its entirety and, if specified, to dmf_compound_contiguous measurement features as shown in Figure 6-12 and Figure 6-15; they apply to these features independently according to ISO 22432 (ISO 2011i). When multiple features are considered with a profile tolerance with in-between or all-around indications, other modifiers are defined to enable the construction of toleranced features such as combined zone (CZ), separate zone (SZ) and united feature (UF) modifiers. These modifiers are recorded in REIMS as the chs_modifier attribute in Figure 6-51. A UF modifier indicates that a dmf_compound_contiguous measurement feature is to be constructed in relation to this characteristic. CZ and SZ modifiers are used to explicitly specify whether the applied tolerance defines a single combined zone for the included features or a set of separate zones for each included feature independently. CZ means all the individual zones are constrained in both location and orientation explicitly or implicitly with respect to each other. The default case for a profile tolerance applied to a group of features is that their tolerance zones are separate, but if a tolerance specifies a group of feature that forms a pattern then the default case is that the zones are combined. Figure 6-57 shows a graphical example of a case where common zone modifier can be applied. REIMS represents combined zone requirements by the combined_tolerance_zone entity as shown in Figure 6-54.

Finally, a projected tolerance zone is indicated when the Ⓟ modifier is used to modify the tolerance value. This modifier indicates that the toleranced feature is either a portion of an extended feature or its related derived feature and the tolerance zone is the zone related to this feature. The projection is considered external to the part for a specified projection length starting from a defined feature. REIMS represents the projected zone as shown in Figure 6-54; in this figure, the projection_end attribute references the shape element from which the tolerance zone is projected and the projection_length defines the projection extent. Figure 6-58 shows an example of the interpretation of a projected tolerance modifier.

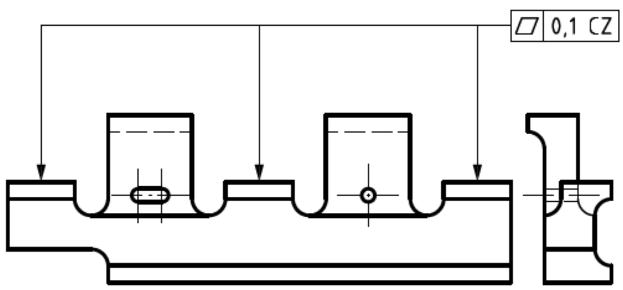


Figure 6-57: Common zone modifier (ISO 2012b)

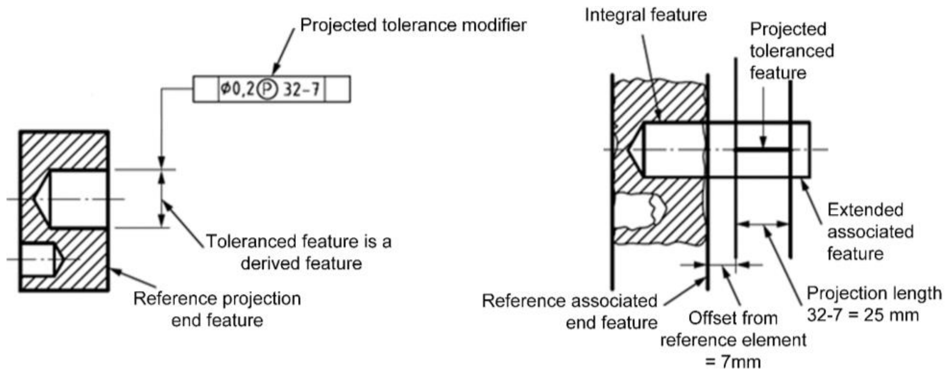


Figure 6-58: Projected tolerance feature and zone (ISO 2012b)

7. The REIMS data model prototype implementation

This chapter describes the realisation of the REIMS prototype implementation (REIMS-PI) for the demonstration of the capabilities of the REIMS data model, presented in chapter 6, within the digital manufacturing. This chapter outlines the realisation process stages and the implementation data flow.

7.1. Implementation scenario description

The implementation flow of the REIMS data model consists of three stages: interaction with the design file; the definition of the measurement process; and, the communication of REIMS data. Figure 7-1 shows the REIMS-PI workflow and its three phases. The input to the implementation framework is a STEP-AP242 file containing part description augmented by tolerances information. The output of the implementation framework is a STEP-compliant physical file containing a REIMS measurement process represented by measurement features and operations. The first implementation phase starts by importing a CAD file using the STEP neutral exchange format into the implementation environment where GD&T data are extracted from the imported file. Next, the REIMS data model is constructed and populated using measurement practice rules or manual data input to define various measurement features and operations. Finally, the REIMS data model is encoded in the form of a STEP part 21 text-file and different communication scenarios for the execution phase are considered based on the available measurement equipment.

7.1.1. Working environment

The REIMS-PI uses Microsoft Visual Studio (MVS) (Microsoft 2013) that is an integrated development environment (IDE) for creating various types of applications from Microsoft. The MVS supports many programming languages for coding with many supporting tools such as code editor and debugger. Examples of supported languages in MVS are C/C++ (via Visual C++), VB.NET (via Visual Basic .NET) and C# (via Visual C#). Various types of applications can be developed using MVS such as win32 console applications, graphical user interface applications, web applications and mobile applications. C++ is the selected programming language for REIMS-PI during the extraction of necessary information from STEP-based CAD files as discussed in subsection 5.1.6. This research develops a console application using C++ as the working environment to obtain required data from the design phase which can be used directly in the measurement phase.

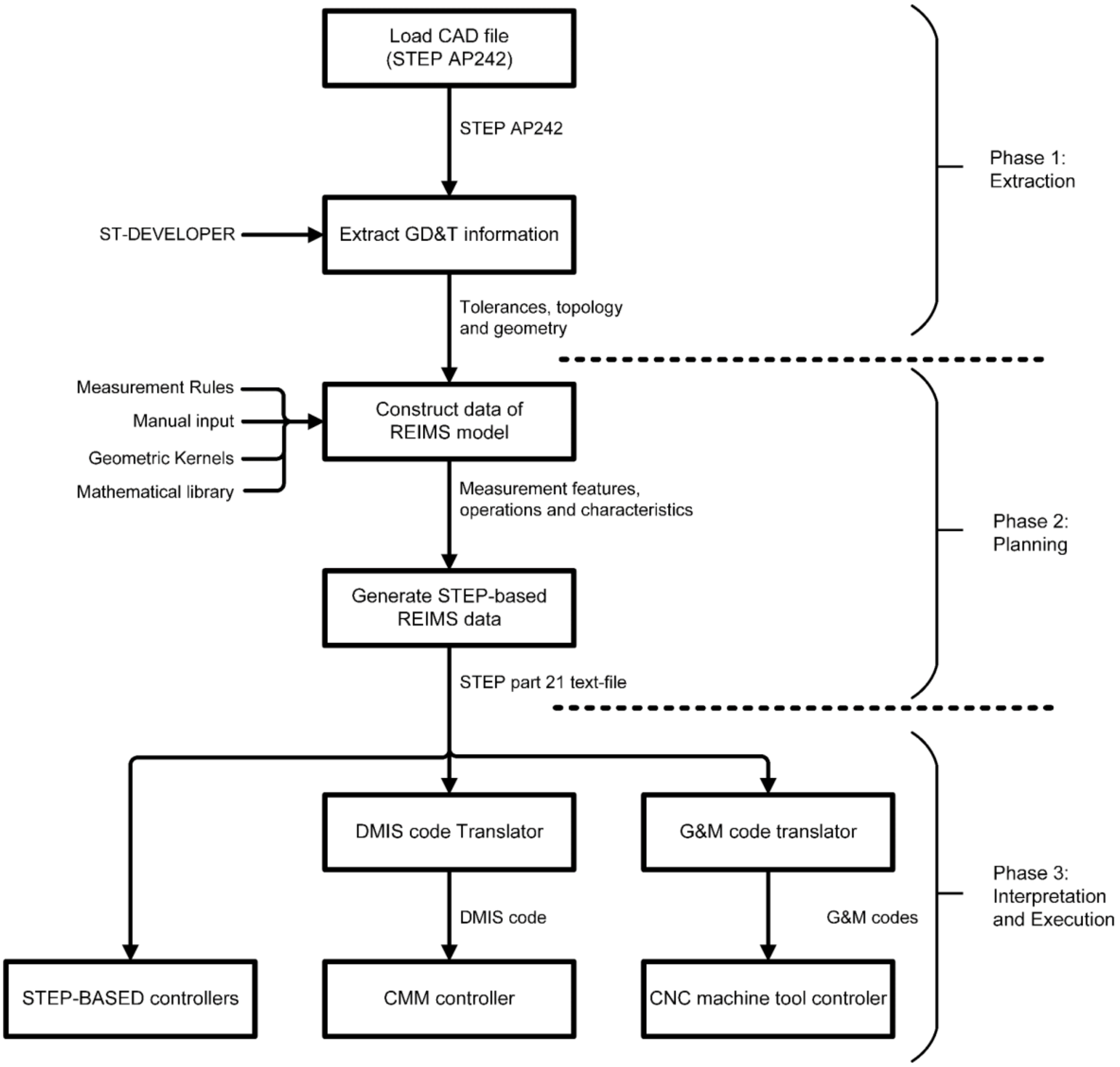


Figure 7-1: REIMS data model implementation flow chart

In addition, the REIMS-PI deploys the ST-Developer personal edition V16.0 (ST-Developer 2014), from STEP Tools Inc. (STEPtools 2016), for the extraction of CAD data. The ST-Developer™ is a software development kit (SDK) for managing STEP and STEP-NC data in digital manufacturing applications. ST-Developer is a C++ library files that can be used within the implementation environment to read and write STEP CAD or CAM data. ST-developer benefits from C++ support for multi-file programs. In multi-files programs, ready-made libraries of functions can be combined and used by other application developers into their applications, which minimises the programming effort needed for creating new applications. The used version of ST- Developer in the REIMS prototype implementations contains 32-bit dynamic link libraries (DLL) for MVS2013. The ST-Developer libraries used in this research are the Merged-CAD library that provides tools to read STEP CAD models including AP203, AP203 e2, AP214 e3 and AP242 definitions. The ST-Developer also provides the Merged-CAM library that adds STEP-NC AP238, AP224 and some AP240 definitions. Figure 7-2 shows the ST- Developer hierarchy and the included libraries. In Figure 7-2, the ROSE library is a core library in ST-Developer that is a C++ application programming interface (API). The Rose library holds EXPRESS-defined data for creating STEP applications that manage and exchanges CAD data saved in the form of STEP physical files. The Rose library provides advanced object search and traversal features, which provides control over STEP physical file data.

7.1.2. Importing and manipulating STEP-based CAD data

During this stage of REIMS-PI, a CAD data file is loaded and necessary GD&T information is extracted from a CAD file using implementation environment described in subsection 7.1.1. The imported CAD data is stored as a STEP-based physical file as defined by STEP AP242. Based on the literature introduced in section 3.1, the STEP AP242 format is selected as being the state-of-the-art format for exchanging the design data. According to the literature, STEP AP242 is the proposed data exchange format for enabling MBD and digital manufacturing. The AP 242 file includes data that represents part geometry, topology and tolerance information. The CTC-01 test case provided by

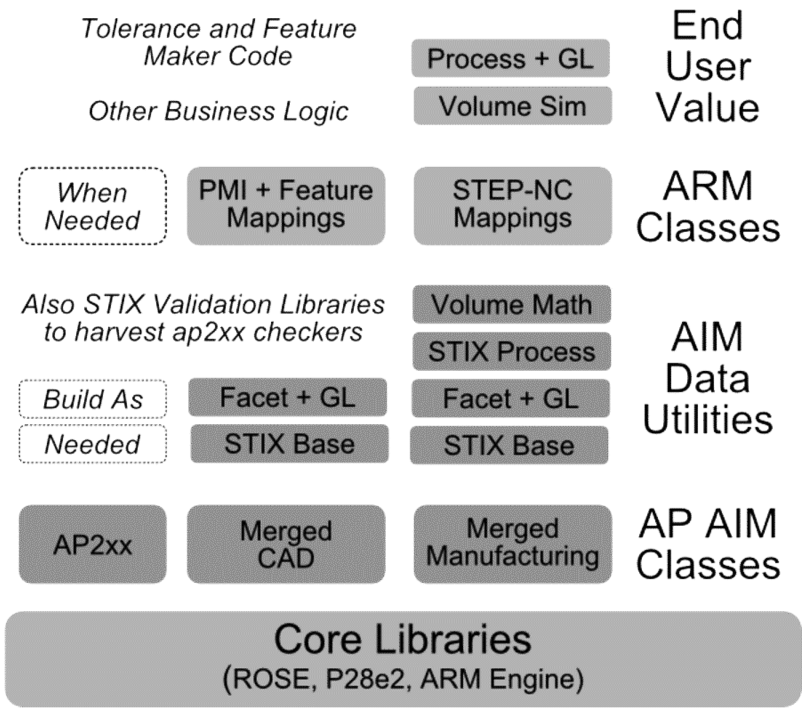


Figure 7-2: ST-Developer hierarchy and included libraries (STEPtools 2016)

NIST in the form of STEP AP242 file is used for testing the REIMS data model implementation. The CTC-01 test case was selected as it was already used for testing the interoperable exchange of design specifications between different CAD systems and hence it is a validated representation (NIST 2013). In addition, The CTC-01 test case includes different types of characteristics that are required for testing the capabilities and limitations of the REIMS-PI. The CTC-1 test case includes twelve geometric characteristics, among them there is only one that is an unrelated characteristic, and seven dimensional characteristics. The prototype implementation in this work uses three different characteristic types among those that exist in the CTC-01 test case. These three characteristics are used for testing the suitability of the REIMS data model for constructing and exchanging measurement process definitions. It should be noted that the same implementation process can be generalised for the other characteristic types in the CTC-01 test case. Figure 7-3 shows the CTC-01 NIST test case used in this research for implementing the REIMS data model and those three characteristics that are selected for REIMS-PI.

7.1.3. Generating REIMS data and generating the part 21 physical file

In REIMS-PI, the extracted information from the STEP-AP242 physical file of the CTC-01 test case is used to produce the nominal integral and derived definitions in the REIMS data model. The nominal measurement features construct necessary links with topological and geometric data in CAD information. In addition, the relationships between derived controlled and deriving elements are explicitly defined. For each defined measurement entity, the measurement extraction and analysis operations are defined manually, or automatically based on measurement best practice and rules.

The measurement extraction operations require information about geometric size and location of the measurement feature. The other measurement analysis operations require the definition of a measurement feature resulting from a preceding operation and the parameters necessary to define data analysis step. The constructed and defined measurement features and operations data are then published as a part 21 physical file as the used mechanism of data exchange. The part 21 file consists of geometry, topology and tolerance data in addition to measurement feature and operation definitions. The measurement process definition is constructed as a subtype of `workplan` and `executable` entities as illustrated in Figure 6-1. It should be mentioned that the measurement sequence defined in REIMS data model can be changed later based on the selected measurement equipment for execution of the measurement process.

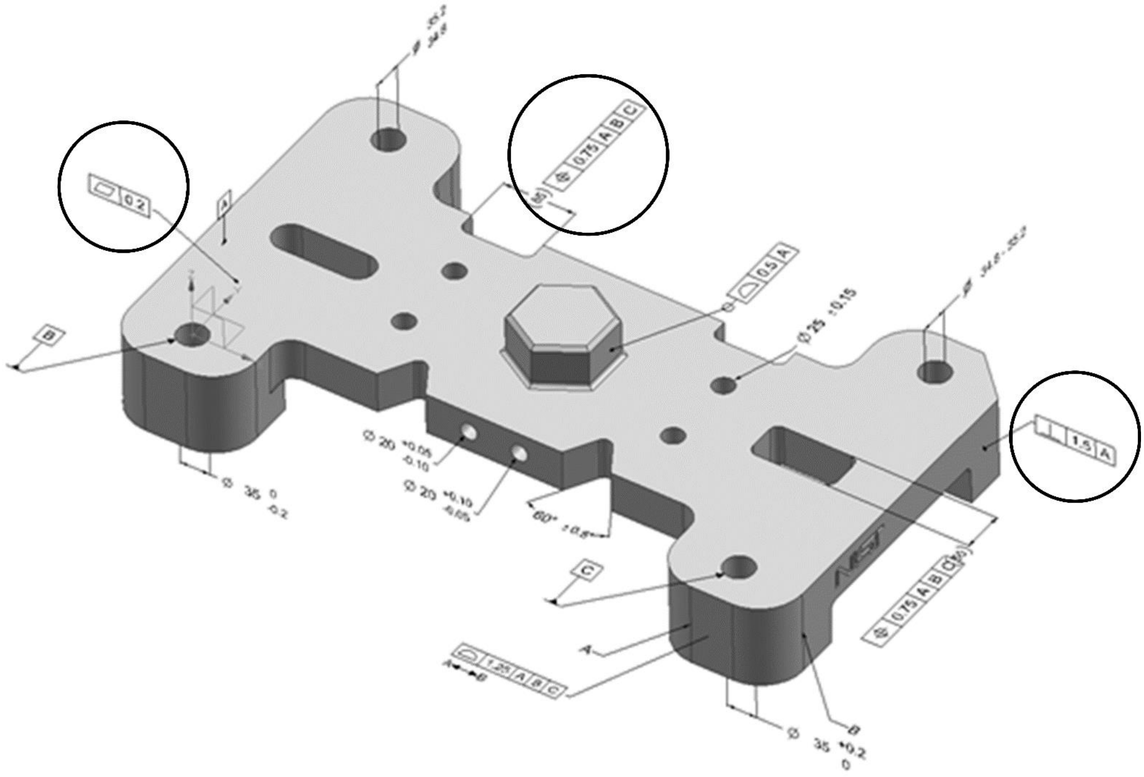


Figure 7-3: The NIST CTC-01 test case (NIST 2013)

7.1.4. Interpreting REIMS data for measurement execution

The execution of the defined measurement process can take two distinct routes. The first is used when a STEP-compliant measurement equipment is used for the measurement execution; in which case, the published file can be loaded directly without interpretation into the measurement equipment controller for measurement execution. The second route requires interpreting the published physical file into one of the used programming languages of legacy measurement equipment. The two routes are considered by REIMS-PI as shown in Figure 7-1.

7.2. Test cases and implementation results

The REIMS-PI focuses on three different specification examples that are circled in Figure 7-3. The flatness and perpendicularity characteristics are both specifying single integral geometric entities, however, the flatness is an unrelated specification while the perpendicularity is a related one that is defined with respect to a datum system. The locational characteristics specify a derived entity that is the situation element of the slot feature; this characteristic requires the collection of both slot side geometric features for the definition of the measurement process. In the following subsections, the implementation flow, illustrated in Figure 7-1, will be discussed for the three selected characteristics circled in Figure 7-3.

7.2.1. Measurement of an integral element with an unrelated characteristic

The first implementation phase is to use the input STEP-AP242 physical file to extract necessary data for defining the related measurement process. The CAX-IF recommended practice (Boy *et al.* 2014), and the ISO STEP-AP238 (ISO 2006b) documents are used for understanding of the AP242 AIM data structure and linkage for enabling data extraction from the physical file. The flatness tolerance circled in Figure 7-3 is an unrelated tolerance that specifies a single integral geometric entity. The traversal map for extracting the flatness tolerance information from the STEP-AP242 file is shown in Figure 7-4. In this figure, the `flatness_tolerance` entity has a `magnitude` attribute that references a `measure_with_unit` entity. This entity references the select data type named `measure_value` that evaluates to `length_measure` with 0.2 real value. The unit component of `measure_with_unit` entity evaluates to SI units that means the flatness tolerance value is 0.2 mm. In addition, the `flatness_tolerance` entity references a `shape_aspect` entity via its `toleranced_shape_aspect` attribute.

The `shape_aspect` entity is not referenced directly as the toleranced geometry serves another role as being a datum feature for datum labelled as “A” in Figure 7-3. A `composite_group_shape_aspect` entity is defined to link the targeted geometry to its two roles that are a toleranced feature and a datum feature. Both the `shape_aspect` and `datum` entities are connected to the `composite_group_shape_aspect` through a `shape_aspect_relationship` entity. The `geometric_item_specific_usage` entity links the `shape_aspect` entity to its `geometric_representation_item` through the related `topological_representation_item` that is the `advanced_face` entity in this case. Finally, the `advanced_face` entity references a `plane` geometric entity that represents the geometry data of the toleranced feature and its outer and inner `edge_loop` entities via the `face_bound` attribute. The plane’s geometric data includes a position and a normal vector while the vertices information is obtained through the underneath edges information. The AP242 part 21 file data representing this traversing map is shown in Figure 7-5. In Figure 7-4, the `advanced_brep_shape_representation` entity represents the modelled part placement and higher-level topology represented by `manifold_solid_brep` and

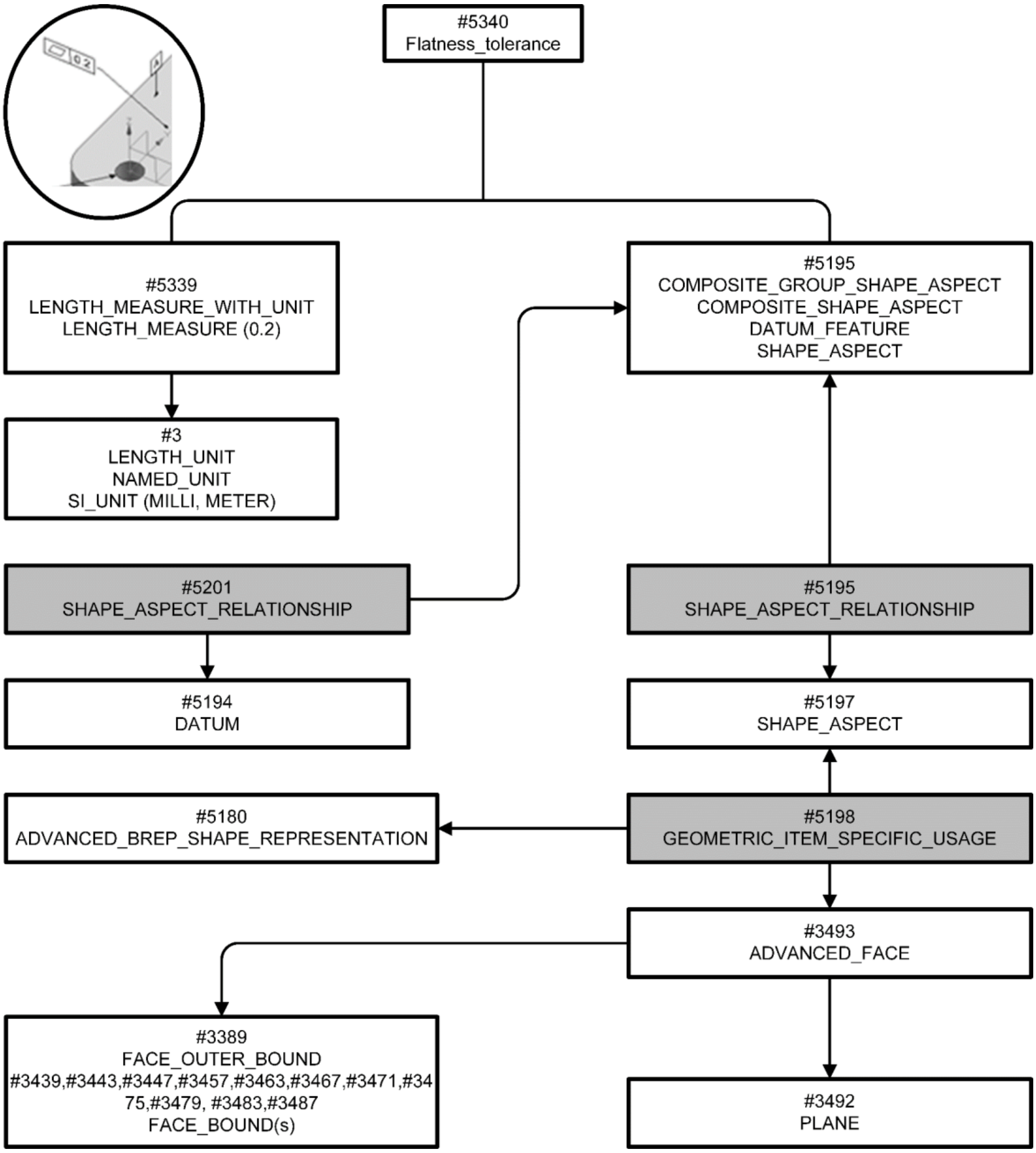


Figure 7-4: Traversal map of the flatness tolerance in the CTC-01 AP242 exchange file

`closed_shell` entities as shown in Figure 7-6. The `closed_shell` entities reference `advance_face` entities that are included in modelled part description.

The extraction phase catches the `flatness_tolerance` entity and traverses through the AP242 physical file data to reach the tolerance value and the toleranced entity information. In this case, and by referring to Figure 6-4, the toleranced entity number #3492 is a single integral entity that is mapped into REIMS as a `dmf_nominal_integral` entity where `its_topology` attribute references the `advanced_phase`, entity number #3493 in Figure 7-4 and Figure 7-5. The extraction

```
#3488=CARTESIAN_POINT('',(0.0,0.0,0.0));
#3489=DIRECTION('',(0.0,0.0,1.0));
#3490=DIRECTION('',(1.0,0.0,0.0));
#3491=AXIS2_PLACEMENT_3D('',#3488,#3489,#3490);
#3492=PLANE('',#3491);
#3493=ADVANCED_FACE('no187133',(#3389,#3439,#3443,#3447,#3457,#3463,#34
67,#3471,#3475,#3479, #3483,#3487),#3492,.T.);
#5133=MANIFOLD_SOLID_BREP('PartBody',#5132);
#5180=ADVANCED_BREP_SHAPE_REPRESENTATION('',(#5179,#5133),#5);
#5194=DATUM('Simple Datum.1',$,#12,.F.,'A');
#5195=(     COMPOSITE_GROUP_SHAPE_ASPECT()     COMPOSITE_SHAPE_ASPECT()
DATUM_FEATURE()         SHAPE_ASPECT('Simple         Datum.1','multiple
elements',#12,.T.) );
#5197=SHAPE_ASPECT('Simple Datum.1',$,#12,.T.);
#5198=GEOMETRIC_ITEM_SPECIFIC_USAGE('','',#5197,#5180,#3493);
#5200=SHAPE_ASPECT_RELATIONSHIP('Simple Datum.1','',#5195,#5197);
#5339=LENGTH_MEASURE_WITH_UNIT(LENGTH_MEASURE(0.2),#3);
#5340=FLATNESS_TOLERANCE('Flatness.1','',#5339,#5195);
```

Figure 7-5: Flatness tolerance data encoded in CTC-01 AP242 exchange file

phase ends by getting the tolerance value, topological entity and the geometric entity attached to the targeted characteristic. Following, the definition of the measurement process starts by defining the necessary data for the extraction measurement operation of the toleranced feature using its topological and geometrical data.

```
#5132=CLOSED_SHELL('no 222183',(
    #55,#79,#555,#597,#669,#702,#733,#766,#813,#878,
    #902,#926,#951,#975,#1039,#1063,#1088,#1112,#1136,#1203,
    #1250,#1283,#1314,#1347,#1387,#1418,#1451,#1498,#1563,#1587,
    #1611,#1636,#1660,#1685,#1709,#1733,#1757,#1782,#1806,#1831,
    #1855,#1879,#1946,#1993,#2026,#2048,#2087,#2104,#2143,#2184,
    #2213,#2254,#2283,#2329,#2375,#2396,#2407,#2428,#2439,#2463,
    #2487,#2504,#2540,#2552,#2588,#2600,#2636,#2654,#2696,#2708,
    #2738,#2756,#2786,#2804,#2834,#2852,#2884,#2908,#2933,#2950,
    #2982,#3006,#3031,#3055,#3080,#3104,#3129,#3146,#3176,#3194,
    #3224,#3242,#3272,#3290,#3320,#3338,#3493,#3550,#3587,#3624,
    #3661,#3698,#3715,#3771,#3802,#3826,#3850,#3874,#3898,#3915,
    #3937,#3954,#3971,#3988,#4005,#4017,#4305,#4336,#4435,#4452,
    #4469,#4486,#4503,#4520,#4537,#4554,#4571,#4588,#4605,#4617,
    #4648,#4672,#4697,#4847,#4864,#4881,#4898,#4915,#4932,#4949,
    #4966,#4983,#5000,#5017,#5034,#5051,#5068,#5085,#5102,#5119,
    #5131));
#5133=MANIFOLD_SOLID_BREP('PartBody',#5132);
#5176=CARTESIAN_POINT('',(0.,0.,0.));
#5177=DIRECTION('',(0.,0.,1.));
#5178=DIRECTION('',(1.,0.,0.));
#5179=AXIS2_PLACEMENT_3D('Reference Axes',#5176,#5177,#5178);
#5180=ADVANCED_BREP_SHAPE_REPRESENTATION('',(#5179,#5133),#5);
```

Figure 7-6: The advanced_brep_shape_representation entity encoded in the CTC-01 AP242 exchange file *(i) Defining the extraction measurement operation*

It is assumed that a contact measurement technology is available for extracting the `advanced_face` entity number #3493. As the `flatness_tolerance` is a form characteristic, the contact scanning technology is appropriate to obtain a reliable assessment of the flatness specification. The parallel profile extraction strategy is used as specified by the ISO 12781-2 (ISO 2011g). In Figure 6-17, the `work_on` attribute of the `extraction_workingstep` entity will reference the `advanced_face` number #3439 while the `its_requirements` attribute will reference two different plane data through the attributes of the `extraction_requirement` entity. The first plane represented by the `its_safety_plane` attribute of the `extraction_requirement` entity defines a safety plane to which the approach and retract movements will be carried on between separate scanning curves. The safety plane is parallel to the toleranced plane by the flatness characteristic and lies above it with 100mm. The second plane is an intersection plane and is represented by the `enabling_plane` attribute of the `enabling_data` entity referenced by the `extraction_requirement` entity. The enabling plane is located at (-75, 0, 0) and has a normal direction of (-1, 0, 0).

The defined enabling plane is incremented to specific positions of the targeted face according to the `specified_strategy` attribute as defined in Figure 6-17. The intersection between the incremented planes and the targeted face determines the scanning curves for extracting the targeted face. The offsetting of the enabling plane and the intersection evaluation can be explicitly defined where necessary using the `transformation_construction` and `intersection_construction` measurement operations as defined in Figure 6-33 and Figure 6-42 respectively. In this implementation, it is assumed that the targeted face scanning curves number and positions are defined manually based on the `enabling_plane` and the `specified_strategy` data. As a result, the `planned_path` attribute of the `extraction_planned_data` entity, shown Figure 6-17, will be populated with a list of ten separated scanning line paths as shown in Figure 7-7. These scanning paths are specified as not being connected through the Boolean attribute of the `path_base_contact_scan` entity, shown in Figure 6-17, that evaluates to `FALSE` and hence the intermediate approach and retract movements are defined at the start and end positions of each scanning lines. The exchange part 21 format of the measurement extraction operation described for extracting the geometric face related to the flatness specification is shown in Figure 7-8. The actual point data recorded from the ten contact

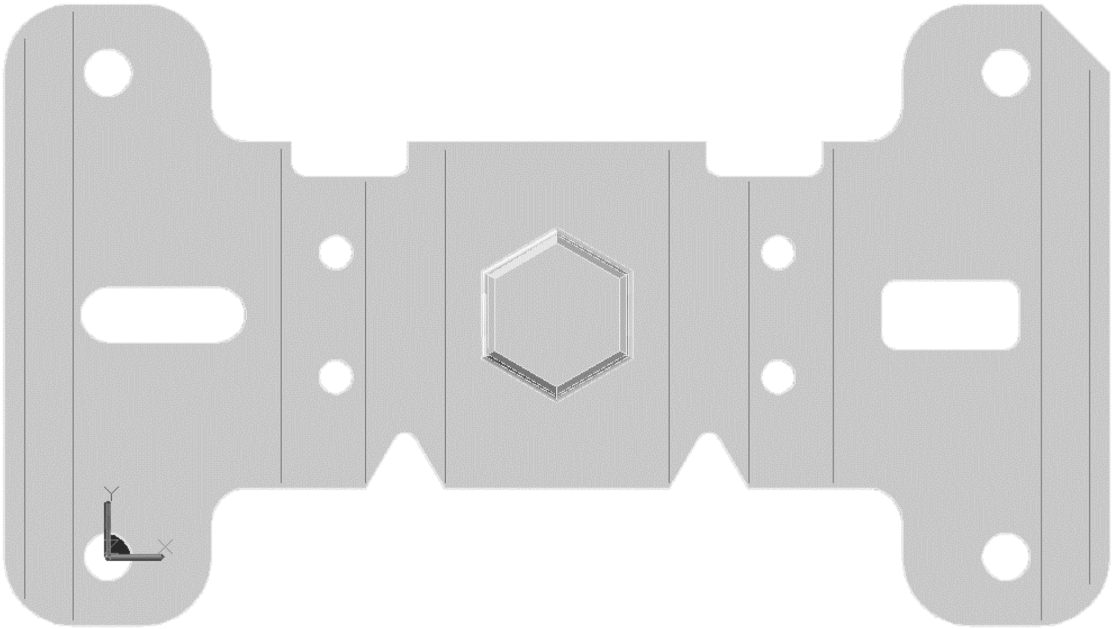


Figure 7-7: scanning lines for the extraction operation related to the flatness tolerance

scanning traces is finally referenced by a single `dmf_specific_extracted_data` entity through its `dmf_point_cloud` attribute. This extracted data entity also references the `extraction_planned_data` entity # 8047 in Figure 7-8 that represents the defined method by which actual data was defined.

(ii) Defining the analysis measurement operations

After the extraction operation has been defined, the reported results from measurement execution phase, actual point data, are collected and recorded as a `dmf_point_cloud` referenced by a `dmf_specific_extracted_data` entity. The evaluation of the flatness tolerance requires the definition of other measurement analysis operations that starts by manipulating the extracted data. For example, the `outlier_removal` operation can be defined when the collected point data includes noise that may need elimination, which is usually the case in optical measurement technology. For form measurement using contact-scanning technology, a filtering measurement operation is necessary to differentiate short and long wavelength components of the gained signal that may affect the final reported roughness, waviness or form values.

For flatness assessment, the filtering operation uses a Gaussian filter and works on the `dmf_specific_extracted_data` actual measurement feature. The used Gaussian filter is a low-pass filter that allows signals with lower frequencies, hence with higher wavelengths than the cutoff value, to be transmitted and the other signals to be

```
#3493=ADVANCED_FACE('no187133',(#3389,#3439,#3443,#3447,#3457,#3463,#34
67,#3471,#3475,#3479, #3483,#3487),#3492,.T.);
#8001=DMF_NOMINAL_INTEGRAL ('DmFlatness 01',#3493);
#8002=CARTESIAN_POINT('',(0.0,0.0,100));
#8003=DIRECTION('',(0.0,0.0,1.0));
#8004=DIRECTION('',(1.0,0.0,0.0));
#8005=AXIS2_PLACEMENT_3D('',#8002,#8003,#8004);
#8006=PLANE('safepl',#8005);
#8007=CARTESIAN_POINT('',(-75.0,0.0,0.0));
#8008=DIRECTION('',(-1.0,0.0,0.0));
#8009=DIRECTION('',(0.0,1.0,0.0));
#8010=AXIS2_PLACEMENT_3D('',#8007,#8008,#8009);
#8011=PLANE('',#8010);
#8012=ENABLING_DATA(#8011,$,$,$);
#8013=EXTRACTION_REQUIREMENT (#8006,$,$,$,#8012);
#8014=DISTANCE_BASED_RATE(0.3, 'mm');
#8015=DIRECTION('approach-dir',(0.0,0.0,-1.0));
#8016=PATH_BASED_CONTACT_SCAN('ExtWs  01',$,#8001,#8013,'PARAPROF',$,$,
#8014, #8015 ,.F.);
#8017=CARTESIAN_POINT('',(-60.0,-30.0,0.0));
#8018=CARTESIAN_POINT('',(-60.0,375.0,0.0));
#8019=LINEAR_MEASUREMENT_PATH('',#8017,#8018);
#8020=CARTESIAN_POINT('',(-25.0,390.0,0.0));
#8021=CARTESIAN_POINT('',(-25.0,-45.0,0.0));
#8022=LINEAR_MEASUREMENT_PATH('',#8020,#8021);
#8023=CARTESIAN_POINT('',(125.0,55.0,0.0));
#8024=CARTESIAN_POINT('',(125.0,294.0,0.0));
#8025=LINEAR_MEASUREMENT_PATH('',#8023,#8024);
#8026=CARTESIAN_POINT('',(186.0,271.0,0.0));
#8027=CARTESIAN_POINT('',(186.0,55.0,0.0));
#8028=LINEAR_MEASUREMENT_PATH('',#8026,#8027);
#8029=CARTESIAN_POINT('',(244.0,55.0,0.0));
#8030=CARTESIAN_POINT('',(244.0,294.0,0.0));
#8031=LINEAR_MEASUREMENT_PATH('',#8029,#8030);
#8032=CARTESIAN_POINT('',(406.0,294.0,0.0));
#8033=CARTESIAN_POINT('',(406.0,55.0,0.0));
#8034=LINEAR_MEASUREMENT_PATH('',#8032,#8033);
#8035=CARTESIAN_POINT('',(464.0,55.0,0.0));
#8036=CARTESIAN_POINT('',(464.0,271.0,0.0));
#8037=LINEAR_MEASUREMENT_PATH('',#8035,#8036);
#8038=CARTESIAN_POINT('',(525.0,294.0,0.0));
#8039=CARTESIAN_POINT('',(525.0,55.0,0.0));
#8040=LINEAR_MEASUREMENT_PATH('',#8038,#8039);
#8041=CARTESIAN_POINT('',(675.0,-45.0,0.0));
#8042=CARTESIAN_POINT('',(675.0,390.0,0.0));
#8043=LINEAR_MEASUREMENT_PATH('',#8041,#8042);
#8044=CARTESIAN_POINT('',(710.0,350.0,0.0));
#8045=CARTESIAN_POINT('',(710.0,-30.0,0.0));
#8046=LINEAR_MEASUREMENT_PATH('',#8044,#8045);
#8047=EXTRACTION_PLANNED_DATA(#8016,#8019,#8022,#8025,#8028,#8031,#8034
,#8037,#8040,#8043,#8046,$);
```

Figure 7-8: REISM exchange format of the extraction data for evaluating the flatness characteristic suppressed; consequently, the `is_shortwavepass` Boolean attribute of the defined filter is set to false as the longer wavelengths are passed. The used cutoff wavelength is 8mm; In fact, the cutoff values for form evaluation is not standardised (Muralikrishnan and Raja 2009), so the upper cutoff standardised limit used for the waviness separation is used as the low-pass cutoff for the form evaluation. The filtered data is stored as a filtered measurement feature represented by a `dmf_flatness` measurement entity that links the resulting point data with the filtering operation definition. The filtering operation as specified in the physical exchange part 21 file is illustrated in Figure 7-9.

Finally, the reference element related to the filtered measurement data is constructed for enabling the final evaluation of the actual flatness value. The reference element is fitted to the filtered data using a `best_fit_construction` measurement operation. The least square Gaussian association is selected with a plane used as the base geometry. The association operation works on the `dmf_flatness` feature and it results in a `dmf_associated` measurement entity that links the resulted plane to the association operation definition. The association is unconstrained as the flatness tolerance is an unrelated specification. The fitting construction operation is specified in the exchange part 21 file as shown in Figure 7-9. The final step is the definition of the evaluation process for the flatness characteristic. The `geometric_chs_evaluation` measurement operation references the evaluated flatness specification in addition to the references associated and the actual filtered measurement entities. The evaluated actual flatness deviation is then recorded as `geometric_deviation` entity that references both the `geometric_chs_evaluation` entity and the reported deviation value. The evaluation operation definition is specified in the physical exchange part 21 file as shown in Figure 7-9.

The REIMS-PI shows how explicitly every single step involves the necessary data for identifying the part surfaces related to a specific characteristic and how both the

```
#8048=DMF_POINT_CLOUD(Reported Data);
#8049=DMF_SPECIFIC_EXTRACTED_DATA('DmEXT 01',#8047,#8048,$);
#8050=NESTING_INDEX(8,.MM.);
#8051=FILTERING_OPERATION(#8049,.GAUSSIAN.,.F.,#8050);
#8052=DMF_POINT_CLOUD(Reported Data);
#8053=DMF_FLATNESS('DmFilt 01',#8051,#8052);
#8054=BEST_FIT_CONSTRUCTION((#8053),.LS.,.PLANE.,$);
#8055=PLANE(Reported Data);
#8056=DMF_ASSOCIATED('DmAssoc 01',#8054,#8055);
#8057=GEOMETRIC_CHS_EVALUATION(#5340,#8056,#8053);
```

Figure 7-9: REIMS exchange format of the analysis operations for evaluating the flatness characteristic needed extraction and analysis measurement operations are defined to evaluate the actual unrelated geometric characteristics. Through the exchange part 21 file, it can be seen how traceability is ensured for every reported feature and value by being connected to their conditions of construction or evaluation.

7.2.2. Measurement of an integral element with a related characteristic

The perpendicularity characteristic, circled in Figure 7-3, is a related characteristic as it is defined with respect to a datum system; including a datum feature controlled by the flatness tolerance discussed in section 7.2.1. The STEP-AP242 traversal map for

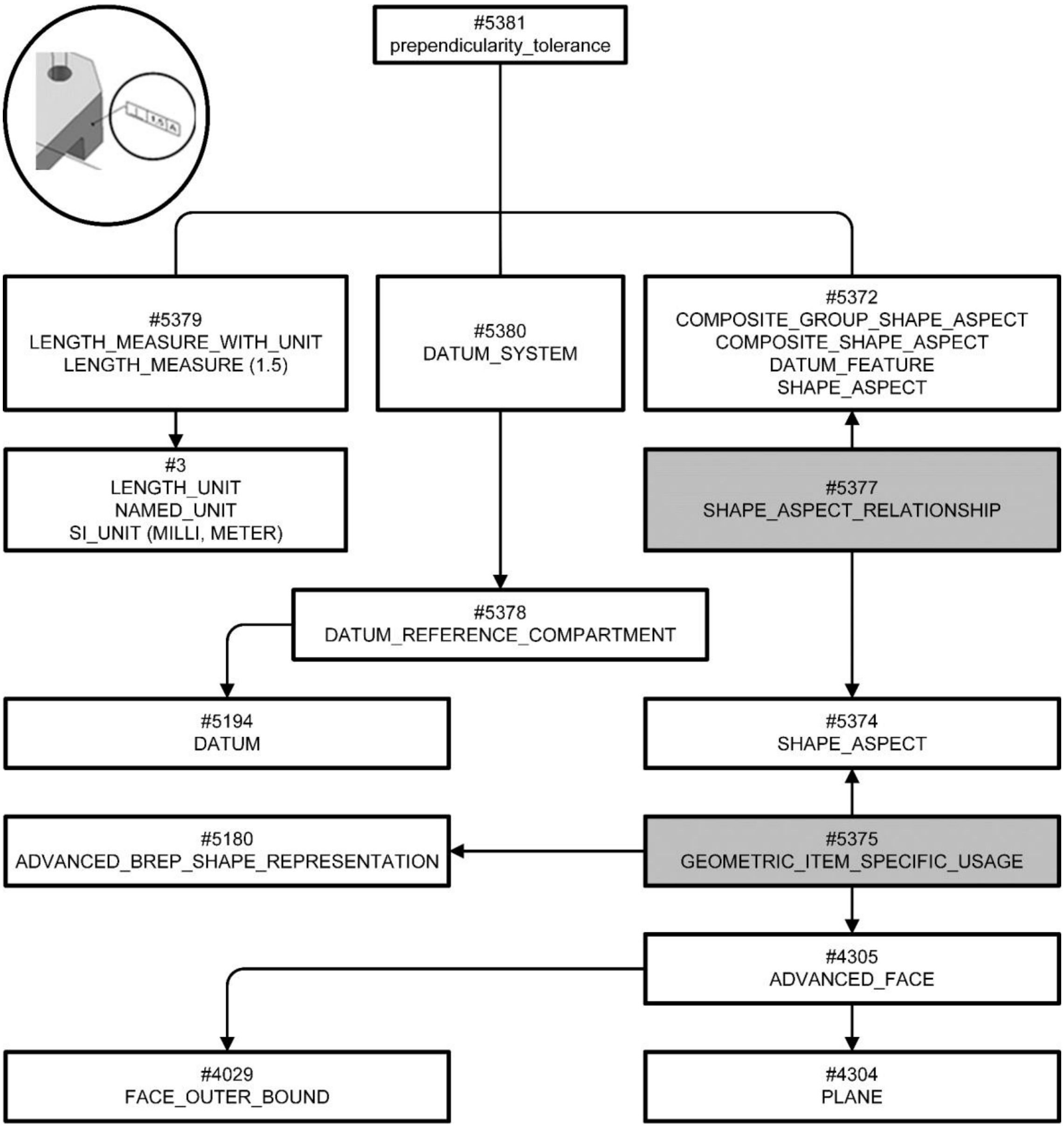


Figure 7-10: Traversal map of the perpendicularity specification in the CTC-01 model

```
#4029=FACE_OUTER_BOUND('',#4028,.F.);
#4300=CARTESIAN_POINT('',(400.0,-175.0,0.0));
#4301=DIRECTION('',(-1.0,0.0,0.0));
#4302=DIRECTION('',(0.0,1.0,0.0));
#4303=AXIS2_PLACEMENT_3D('',#4300,#4301,#4302);
#4304=PLANE('',#4303);
#4305=ADVANCED_FACE('no 222293',(#4029,#4304,.F.);
#5133=MANIFOLD_SOLID_BREP('PartBody',#5132);
#5177=DIRECTION('',(0.,0.,1.));
#5176=CARTESIAN_POINT('',(0.,0.,0.));
#5178=DIRECTION('',(1.,0.,0.));
#5179=AXIS2_PLACEMENT_3D('Reference Axes',#5176,#5177,#5178);
#5180=ADVANCED_BREP_SHAPE_REPRESENTATION('',(#5179,#5133),#5);
#5194=DATUM('Simple Datum.1',$,#12,.F.,'A');
#5372=COMPOSITE_GROUP_SHAPE_ASPECT('Perpendicularity.1','multiple
elements',#12,.T.);
#5374=SHAPE_ASPECT('Perpendicularity.1',$,#12,.T.);
#5375=GEOMETRIC_ITEM_SPECIFIC_USAGE('','',#5374,#5180,#4305);
#5377=SHAPE_ASPECT_RELATIONSHIP('Perpendicularity.1','',#5372,#5374);
#5378=DATUM_REFERENCE_COMPARTMENT('',$,#12,.F.,#5194,$);
#5379=LENGTH_MEASURE_WITH_UNIT(LENGTH_MEASURE(1.5),#3);
#5380=DATUM_SYSTEM('',$,#12,.F.,(#5378));
#5381=PERPENDICULARITY_TOLERANCE('Perpendicularity.1','',#5379,#5372,(#
5380));
```

Figure 7-11: Perpendicularity specification encoded in CTC-01 AP242 exchange file

getting the data related to the perpendicularity characteristic is as shown in Figure 7-10 and the exchange format of this traversed data is as shown in Figure 7-11. The link between the tolerance specification and the controlled geometric entity is as described for the flatness tolerance in section 7.2.1. However, a `datum_system` entity is referenced as an attribute of the `prependicularity_tolerance` entity as it is a related specification. A `datum_system` entity can reference one to three different `datum_reference_compartment` entities; for perpendicularity tolerance, just one compartment is referenced. A `datum_reference_compartment` is finally linked to the `datum` entity as shown in Figure 7-10. This `datum` entity is connected to its geometric surface data that represents the datum feature via a `shape_aspect_relationship`, entity #5201 in Figure 7-4. The datum feature for this datum is the feature controlled by the flatness tolerance discussed in section 7.2.1 and labelled as datum “A” in Figure 7-3.

(i) Defining the extraction measurement operation

For the measurement evaluation of a related specification, both controlled feature and datum feature require extractions. The datum feature was already checked as being extracted as the required extraction operation has been defined as discussed in section

7.2.1. On the other hand, different construction operations are required for the reference element representing the datum feature, as it should be constrained by being outside the part material. The controlled feature is of planar geometry that could be extracted by the same contact measurement technology used for the flatness specification evaluation. Contact scanning technology may not be needed, as perpendicularity is not a form specification and hence a number of measurement points are specified for its evaluation. The edges and the corner vertices of the `advanced_face` number `#4305` are obtained from the exchange data file and are passed to the extraction algorithm with a specified uniform extraction strategy for evaluating the necessary measurement point locations of the plane.

Three points on three parallel lines were recommended for measuring a plane (Flack 2014). Only eight points are used for extracting the planar face to accommodate the slot opening as illustrated in Figure 7-12. Figure 7-13 presents the exchange format for the defined extraction operation where a nominal-integral measurement entity is defined to reference the controlled `advanced_face` by the perpendicularity specification. Later, a `point_based_extraction_operation` is defined for holding the extraction data; this entity references the `dmf_nominal_integral` entity and defines a uniform extraction strategy with eight measurement points. A planning algorithm uses this data to report nominal coordinates of the measurement points that are represented by the `dmf_nominal_extracted` entity in Figure 7-13. These points are linked to the specified conditions used for their

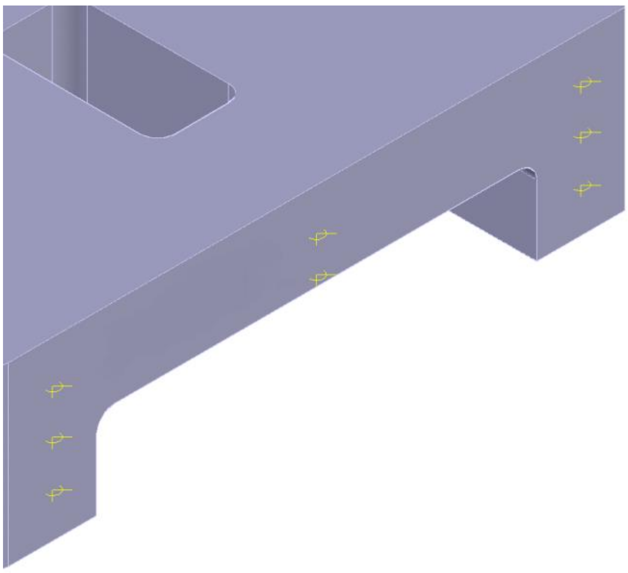


Figure 7-12: sampling points for the extraction operation related to the perpendicularity specification

```
#4305=ADVANCED_FACE('no 222293',(#4029,#4304,.F.);
#8058=DMF_NOMINAL_INTEGRAL('DmfPrep 02',#4305);
#8059=CARTESIAN_POINT('',(735.0,-50.0,0.0));
#8060=DIRECTION('',(1.0,0.0,0.0));
#8061=DIRECTION('',(0.0,1.0,0.0));
#8062=AXIS2_PLACEMENT_3D('',#8059,#8060,#8061);
#8063=PLANE('safepl',#8062);
#8064=EXTRACTION_REQUIREMENT(#8063,$,$,$,$);
#8065=POINT_BASED_EXTRACTION('ExtWs02',$,#8058,#8064,'UNIFORM',8);
#8066=CARTESIAN_POINT('',(725.0,25.0,-24.0));
#8067=CARTESIAN_POINT('',(725.0,25.0,-49.0));
#8068=CARTESIAN_POINT('',(725.0,25.0,-75.0));
#8069=CARTESIAN_POINT('',(725.0,175.0,-24.0));
#8070=CARTESIAN_POINT('',(725.0,175.0,-49.0));
#8071=CARTESIAN_POINT('',(725.0,325.0,-24.0));
#8072=CARTESIAN_POINT('',(725.0,325.0,-49.0));
#8073=CARTESIAN_POINT('',(725.0,325.0,-75.0));
#8074=dmf_nominal_extracted
(#8066,#8067,#8068,#8069,#8070,#8071,#8072,#8073);
#8075=EXTRACTION_PLANNED_DATA(#8065,$,#8074);
```

Figure 7-13: REIMS exchange format of the extraction data for evaluating the perpendicularity characteristic

creation using the `extraction_planned_data` entity. The measurement path can be derived, as the contact measurement sensor should approach each measurement point from the specified safety plan and perpendicular to the measurement surface. After the extraction of the point data, the measurement sensor should then retract in the opposite direction to the safety plane. Finally, the measurement sensor moves along the safety plane to the position where the next measurement point will be approached.

(ii) Defining the measurement analysis operation for both datum and measured features

For a related specification, processing operations for the extracted data of both datum and controlled features need to be defined. The actual data is represented by the `dmf_specific_extracted_data` entities `#8048` for the datum feature, and `#8077` for the controlled feature. A constrained-association operation is defined for the actual data of the datum feature for constructing its reference element that represents datum “A”. In addition, a constrained association operation is defined for constructing the reference element of the controlled feature being perpendicular to the reference element of the datum “A”. The exchange format of both construction operations is as defined by entities #8079 and #8083 in Figure 7-14. Finally, the evaluation operation for the perpendicularity specification is defined by referencing the specification entity in the CAD data in addition to the actual and reference elements of the controlled plane as in entity #8086 in Figure 7-14.

```
#8076=DMF_point_cloud(Reported Data);
#8077=DMF_SPECIFIC_EXTRACTED_DATA('DmEXT 02',#8075,#8076,$);
#8078=MATERIAL_CONSTRAIN($,.T.);
#8079=BEST_FIT_CONSTUCTION((#8049),.MinMax.,.PLANE.,#8078);
#8080=PLANE(Reported Data);
#8081=DMF_ASSOCIATED('DmAssoc 02',8079,#8080);
#8082=ANGLE_CONSTRAIN(#8081,90);
#8083=BEST_FIT_CONSTUCTION((#8077),.LS.,.PLANE.,#8082);
#8084=PLANE(Reported Data);
#8085=DMF_ASSOCIATED('DmAssoc 03',#8083,#8084);
#8086=GEOMETRIC_CHS_EVALUATION(#5381,#8085,#8077);
```

Figure 7-14: REIMS exchange format of the analysis operations for evaluating the perpendicularity characteristic

7.2.3. Evaluation of a Derived entity with a related characteristic

The position characteristic, circled in Figure 7-3, is a related characteristic as it is defined with respect to a datum system. The STEP-AP242 traversal map for obtaining the data related to this position characteristic is shown in Figure 7-15 and the exchange format of this traversed data is shown in Figure 7-16. This geometric characteristic controls the position of a derived entity that is related to two different integral entities. The integral entities should be both linked to the specification that controls their derived entity. The AP242 exchange file uses the composite_group_shape_aspect mechanism to link the geometric specification to both of the parent faces through shape_aspect_relationship entities as shown in Figure 7-15. This geometric characteristic also references a datum system that includes three different datum compartments to hold three different datum entities. The data linkage between the datum system and the included datum features are as discussed in section 7.2.2.

(i) Defining the extraction measurement operation

The obtained data from the design file is first mapped to the REIMS data model by creating a dmf_situation_based entity. This measurement entity then explicitly references the definition of the parent and derived entities related to the position tolerance as shown in Figure 7-17. According to ISO14660 (ISO 2000), the evaluation of a specification that controls a derived measurement feature needs the constructed actual-derived and the reference-derived features to be obtained. The associated reference median plane can be derived mathematically using the geometric information of the two LS-associated planes to the extracted data of the nominal integral entities #8079 and #8080. The extraction and LS association operation of a plane geometry is as described in the previous sections. The datum features also require extraction and constrained construction of datum reference elements as applicable; the datum elements

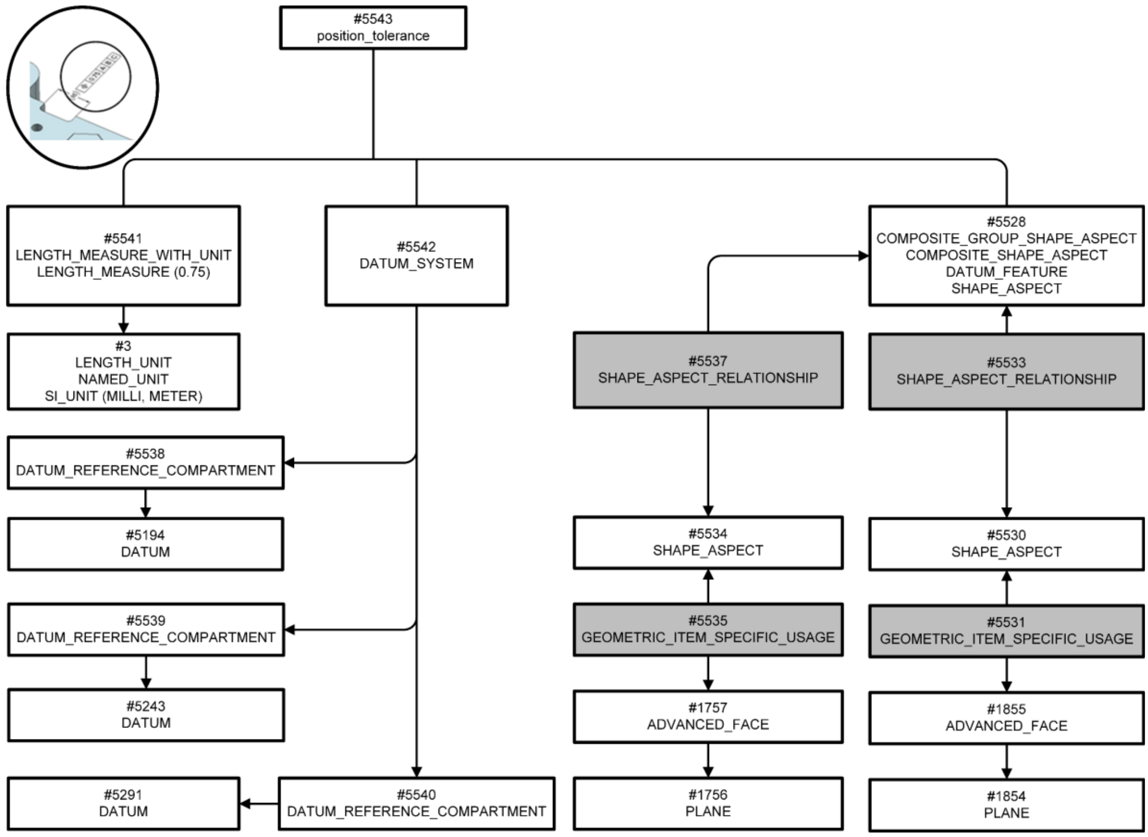


Figure 7-15: traversal map of the position specification in the CTC-01 model

are constructed as described in the perpendicular specification case in section 7.2.2. The construction of the datum reference entities should respect constraints between each constructed datum entity and the preceding constructed datums.

```
#1756=PLANE('',#1755);
#1757=ADVANCED_FACE('no181717',(#1751),#1756,.T.);
#1854=PLANE('',#1853);
#1855=ADVANCED_FACE('no 184141',(#1849),#1854,.T.);
#5194=DATUM('Simple Datum.1',$,#12,.F.,'A');
#5243=DATUM('Simple Datum.8',$,#12,.F.,'B');
#5291=DATUM('Simple Datum.9',$,#12,.F.,'C');
#5530=SHAPE_ASPECT('Position.3',$,#12,.T.);
#5531=GEOMETRIC_ITEM_SPECIFIC_USAGE('','',#5530,#5180,#1855);
#5533=SHAPE_ASPECT_RELATIONSHIP('Position.3','',#5528,#5530);
#5534=SHAPE_ASPECT('Position.3',$,#12,.T.);
#5535=GEOMETRIC_ITEM_SPECIFIC_USAGE('','',#5534,#5180,#1757);
#5537=SHAPE_ASPECT_RELATIONSHIP('Position.3','',#5528,#5534);
#5538=DATUM_REFERENCE_COMPARTMENT('',$,#12,.F.,#5194,$);
#5539=DATUM_REFERENCE_COMPARTMENT('',$,#12,.F.,#5243,$);
#5540=DATUM_REFERENCE_COMPARTMENT('',$,#12,.F.,#5291,$);
#5541=LENGTH_MEASURE_WITH_UNIT(LENGTH_MEASURE(0.75),#3);
#5542=DATUM_SYSTEM('',$,#12,.F.,(#5538,#5539,#5540));
#5543=(GEOMETRIC_TOLERANCE('Position.3','',#5541,#5528)GEOMETRIC_TOLERA
NCE_WITH_DATUM_REFERENCE((#5542)) POSITION_TOLERANCE() );
```

Figure 7-16: Position tolerances encoded in CTC-01 AP242 exchange file

```
#8087=DMF_NOMINAL_INTEGRAL('Dmfpos 03',#1757);
#8088=DMF_NOMINAL_INTEGRAL('Dmfpos 04',#1855);
#8089=DMF_NOMINAL_DERIVED ('midPl 01',#8087,#8088);
#8090=dmf_situation_based(.T.,DMF_COLLECTION((8087,8088),#8089);
#8091=POINT_BASED_EXTRACTION_OPERATION('ExtWs03',$,#8087,$,'UNIFORM',4);
#8092=CARTESIAN_POINT('',( 132.5,290 ,-16.66667));
#8093=CARTESIAN_POINT('',( 132.5, 290.0,-33.33333));
#8094=CARTESIAN_POINT('',( 132.5, 295.0,-16.66667));
#8095=CARTESIAN_POINT('',( 132.5, 295.0,-33.33333));
#8096=dmf_point_cloud((#8092,#8093,#8094,#8095),$,.T.,$,.F.);
#8097=DM_NOMINAL_EXTRACTED('',#8096);
#8098=EXTRACTION_PLANNED_DATA(#8091,#8097);
#8099=POINT_BASED_EXTRACTION_OPERATION('ExtWs03',$,#8088,$,'UNIFORM',4);
#8100=CARTESIAN_POINT('',( 217.5, 290.0,-16.66667));
#8101=CARTESIAN_POINT('',( 217.5, 290.0,-33.33333));
#8102=CARTESIAN_POINT('',( 217.5,295.0 ,-16.66667));
#8103=CARTESIAN_POINT('',( 217.5, 295.0,-33.33333));
#8104=dmf_point_cloud((#8100,#8101,#8102,#8103),$,.T.,$,.F.);
#8105=DM_NOMINAL_EXTRACTED('',#8104);
#8106=EXTRACTION_PLANNED_DATA(#8099,#8105);
#8107=CARTESIAN_POINT(Reported Data);
#8108=CARTESIAN_POINT(Reported Data);
#8109=CARTESIAN_POINT(Reported Data);
#8110=CARTESIAN_POINT(Reported Data);
#8111=DMF_point_cloud((#107,#8108,#8109,#8110),$,.T.,$,.F.);
#8112=DMF_SPECIFIC_EXTRACTED_DATA('DmEXT 03',#8098,#8111,$);
#8113=CARTESIAN_POINT(Reported Data);
#8114=CARTESIAN_POINT(Reported Data);
#8115=CARTESIAN_POINT(Reported Data);
#8116=CARTESIAN_POINT(Reported Data);
#8117=DMF_point_cloud((#8113,#8114,#8115,#8116),$,.T.,$,.F.);
#8118=DMF_SPECIFIC_EXTRACTED_DATA('DmEXT 04',#8106,#8117,$);
#8119=MID_CONSTRUCTION(#8107,#8113);
#8120=CARTESIAN_POINT(Evaluated Data);
#8121=MID_CONSTRUCTION(#8108,#8114);
#8122=CARTESIAN_POINT(Evaluated Data);
#8123=MID_CONSTRUCTION(#8109,#8115);
#8124=CARTESIAN_POINT(Evaluated Data);
#8125=MID_CONSTRUCTION(#8110,#8116);
#8126=CARTESIAN_POINT(Evaluated Data);
#8127=DMF_point_cloud((#8120,#8122,#8124,#8126),$,.T.,$,.F.);
#8128=DMF_DERIVED_EXTRACTED_DATA('DmEXT 05',$,#8127,$);
#8129=ANGLE_CONSTRAIN($,0);
#8130=DISTANCE_CONSTRAIN($,85);
#8131=BEST_FIT_CONSTRUCTION((#8087,#8088),.LS.,.PLANE.,(#8129,#8130);
#8132=PLANE(Evaluated Data);
#8133=PLANE(Evaluated Data);
#8134=DMF_ASSOCIATED('DmAssoc 04',#8131,#8132);
#8135=DMF_ASSOCIATED('DmAssoc 05',#8131,#8133);
#8136=MID_CONSTRUCTION(#8134,#8135);
#8137=PLANE(Evaluated Data);
#8138=DMF_CONSTRUCTED('DmConst 01',#8136,#8137);
#8139=GEOMETRIC_CHS_EVALUATION(#5543,#8138,#8128);
```

Figure 7-17: REIMS exchange format of the measurement operations for evaluating the position characteristic

For constructing the actual extracted median-plane feature, four actual and uniformly distributed points are collected on each side plane. The mid-point of each two opposite points on the slot side-faces is constructed. The collection of these mid-points represents the `dmf_derived_extracted_data` measurement feature. The reference element of the median plane is evaluated as the mid-plane of the two associated side planes of the slot. The reference elements of the slot sides are constructed together with a parallelism and TED constraints. A comparison step is defined to compare the extracted derived data to the reference median plane to evaluate the conformance of the locational specification. The exchange format for these measurement features and operations is shown in Figure 7-17.

8. Discussion

The role of the measurement process has evolved over time within industry. Measurement is not only used for checking product conformance, but also to control manufacturing processes (Morse *et al.* 2016). In addition, measurement assists design decisions by evaluating initial design prototypes (Söderberg *et al.* 2016). Measurement technologies have also evolved (Weckenmann *et al.* 2009; Savio *et al.* 2007); there are many different measurement systems and technologies available today. Integrating measurement in an interoperable way within a product lifecycle is necessary to ensure seamless data flow between measurement and other manufacturing activities to increase measurement throughput (Savio *et al.* 2016; Savio *et al.* 2014). This research aimed to realise an interoperable resource-independent definition of the measurement process in order to reduce the variabilities initiated within the measurement process definition stage, and to benefit economically from measurement interoperability. In the course of the research and in achieving the defined objectives in section 2.3, a number of challenges were identified and addressed as follows:

8.1. Measurement research gaps

In continuation to the academic research for using tolerance information presented in section 3,1, the standards community struggles to define a complete representation of the product design that includes the PMI data and hence uses the MBD as an authoritative 3D model that can be utilised directly by downstream applications (Fischer *et al.* 2015). The author supported the view that by adopting MBD in digital manufacturing, the measurement plans can be defined and executed more efficiently (Quintana *et al.* 2010). According to the literature presented in section 4.1.5, the STEP-AP242 (ISO 2014a) is the state-of-the-art MBD standard format that represents design data augmented with PMI and visualisation information.

Today, AP242 has replaced AP203 (ISO 2011c) and AP 214 (ISO 210a) in the modified STEP framework. In addition, it also has been tested for ensuring design data interoperability between CAD systems (Lipman and Lubell 2015; Frechette *et al.* 2013); however, it has not yet been evaluated from the measurement process perspective (Fisher *et al.* 2015). The author recognised that the REIMS framework should match the recent developments in MBD standardisation and hence STEP AP242 exchange file of the CTC-01 test case was selected for representing part geometrical and tolerance information during the REIMS implementation as shown in Figure 7-1.

The author identified in section 3.1.2 the effect of the deviation of the applied coordinate metrology methods from the standardised definitions of measurement specifications; this deviation affects the uncertainty of the final measurement results (Ballu *et al.* 2015; Vemulapalli *et al.* 2013). The author has referred this deviation to the absence of good measurement practise guides and to the lack of representation of measurement analysis operations included in coordinate metrology practise in the current standardised measurement data models, as identified in section 3.2.3, 4.1.7 and 4.1.8. Consequently, the developed REIMS system in this work aimed to reduce such variabilities through representing the necessary measurement operations required for evaluating the measurement extracted data. The specification of these measurement operations is necessary to provide the measurement operator with proper tools to analysis the measured data according to standardised definitions of design specifications.

Furthermore, the author has recognised that the developed planning systems in the academic literature are resource-dependent which is against the measurement interoperability goal (Zhao *et al.* 2011b). As a result, this work aimed to formalise resource-independent measurement specifications; however, during the course of this research, it was concluded that the planning for the measurement extraction phase should be based on preselected sensor technology. This is why REIMS has been seen as an extension to the same strategy followed by the STEP-NC (ISO 2003) during its developments (Vichare *et al.* 2009; Nassehi 2007). Following the same strategy in REIMS, a measurement plan can be defined in a resource-independent manner but, at some point the used measurement technology should be identified regardless of the measurement equipment that holds this sensor technology.

According to the standardised literature presented in chapter 4, the author supported to the view that a measurement process definition should be formulated in a STEP-based manner (Brecher *et al.* 2006). STEP is an extensive repository of data models that serves various manufacturing contexts (Xu and Nee 2009; Kramer and Xu 2009). As a result, STEP was selected as the modelling framework for REIMS to ensure its direct integrity with design and machining data represented within the STEP framework. By using STEP, REIMS has the advantage of considering design and machining context in a better and more efficient way compared to currently applied standards such as DMIS (ISO 2010c) and QIF (ANSI 2014), as illustrated in Table 4-7.

The ISO GPS series has been introduced along with the surveyed theoretical concepts within its framework. ISO GPS is the ISO standard series that considers design and verification in relation to each other. The author has based on ISO GPS documents during the understanding and analysis phase of this research to identify the measurement data requirements that need to be defined within REIMS data model. The author has identified that the concept introduced in the ISO GPS standards are formatted in a text-based manner that need to be structured in a computer readable format to enable its applicability and benefits for digital manufacturing systems (Bllau *et al.* 2015). The REIMS is designed by modelling these theoretical concepts for representing both measurement features, measurement operations and design characteristics.

8.2. Achieving the REIMS requirements

The key pillar in REIMS for ensuring interoperability is the resource independence philosophy and the dependence on a well-verified STEP exchange format. This research aimed to define a fully resource-independent form of measurement specification, however, this was limited by the need to identify the used measurement technology. This argument is based on the fact that if the measurement sensors are considered as technologies rather than resources then the REIMS is considered as resource-independent but, technology specific in a manner similar to how STEP-NC defines turning and milling operations as technologies. The author's strategy was to consider contact and non-contact measurement technologies for example, turning and milling technologies in STEP-NC framework.

The designed REIMS data model provides a computer interpretable format for the defined measurement features, measurement operations and characteristics presented theoretically in ISO GPS documents. This is a unique aspect of the REIMS data model compared to previously defined measurement data models which are based on the DMIS (ISO 2010c) definitions. ISO GPS extensively breaks down the design and verification requirements which enabled the author to identify necessary data requirements for building up the REIMS data model. In addition to the ISO GPS standard documents, the ASME Y14.5 (ASME 2009) standard was used during the extensive analysis and understanding of design specification to define all possible cases of measurement features. Understanding the STEP framework and analysing the ISO GPS and ASME documents was a major challenge that has been overcome during the course of this research.

Furthermore, attempts were made to make sure that the REIMS data model is universal; that is to have the flexibility to represent measurement process for various measurement scenarios and purposes. The challenge was to select the appropriate constraints to make sure the integrity of a given population of entities represents a given measurement scenario. Constraints, which are normally explicit, were relaxed using optional attributes to allow for the required flexibility. This flexibility combined with the resource-independent philosophy in REIMS would also enable more effective scheduling based on the availability of measurement resources during the execution stage; as complex scenarios may be modelled in such a manner that they can be carried out by various combinations of measurement resources as required.

The author views the REIMS data model as an authorative definition of the measurement plan and as a mechanism to ensure consistency of measurement processes executed at diferent locations in distributed manufacturing environments. The REIMS data model is doing so throught the elimination of the need of any subjective decisions taken during the planning phase. The developed REIMS data model is proposed as a replacement data model for STEP-NC part 16 (ISO14649-16) and with further extensions for representing results, the REIMS framework has the potential to replace STEP AP219 (ISO10303-219).

8.3. Prototype implementation and results

The prototype implementation consisted of three stages described in Figure 7-1. The implementation started by extracting the design data which is then mapped into measurement features. The NIST CTC-01 test case was used as an input design for the implementation framework and this test case was selected as a pre-validated representation of the PMI data (NIST 2013). It includes different types of characteristics that are sufficient for testing the REIMS prototype capabilities. The CTC-01 is used in the STEP SP242 format to cope with the state-of-the-art in MBD standard developments. The REIMS-PI showed that the AP242 data exchange format provides the necessary data and associations for guiding the measurement planning phase, but it would need to be extended to cope with recent concepts introduced in ISO GPS.

Following this, a series of extraction and analysis measurement operations were defined for each measurement feature based on the author’s knowledge and experience. In future, if there will be any standardised measurement good practice and rules, this could be easily coded to automate the construction of measurement operations for each measurement feature. The implementation can list the defined measurement operations for each features but, the sequencing through which the measurement feature is evaluated is left for the algorithms of the used CAIP system.

Finally, A part 21 (ISO10303-21) file, was constructed that could be used to exchange measurement process data between various CAIP applications for the execution phase. Although commercial products in this domain that can interpret part 21 files are rare (the author is not aware of a STEP-compliant CMM, for example), it is possible to translate the contained data to the required format as shown in research in other domains such as machining. On the other hand, selecting another format (interpretable by a given machine) would seriously undermine the interoperable philosophy of this research and therefore the decision was taken to adopt the more difficult to execute, but the more universal approach for encompassing the measurement plan data.

The challenges faced during the implementation were mainly the efforts and time spent in unerstanding the documentation of the ST-Developer personal edition V 16.0 (ST-Developer 2014) to extract data from AP242 part21 file of the CTC-01 test case. In addition, The efforts done for mapping the design specification into the measurement features definedin REIMS based on the ISO GPS definitions.

8.4. Contribution to measurement planning and execution knowledge

The main novelty of this research is the resource-independent philosophy and the generalised approach followed for representing measurement processes to ensure its interoperability and applicability. The REIMS design approach is different to that of QIF and AP219. In these standards, DMIS was considered as the starting point. As DMIS is a tightly resource dependent programming language, the resulting data models are still bound to specific resources. In modelling REIMS, on the other hand, the measurement and design standard documents were analysed at multiple levels and from various perspectives to identify data requirements for the REIMS data model. These system analysis strategy was considered from a novel and unique perspective that is not affected by constraints imposed by resource-based and single-purpose measurement data models as was the case for measurement standards based on DMIS.

It is also noteworthy to mention that REIMS is a STEP-based measurement model that considers both design and machining contexts compared to DMIS and QIF standards. Considering measurement working steps in parallel and in a similar manner to manufacturing ones would allow these operations to be tightly integrated and linked within a coherent framework. The REIMS data model also overcome limitations recognised in both STEP-NC part 16 and STEP AP219 models.

Other novel aspects of REIMS include the consideration of previously ignored technologies such as continuous contact scanning and non-contact extraction operations in data modelling. In addition, the definition, as for the first time, of the necessary data required for measurement analysis operations as well as respecting reverse engineering needs is included within REIMS data model.

8.5. Limitations of the research

The proposed REIMS framework is limited to prismatic parts, however, its design approach allows for the representation of measurement features and operations for free-form features as the used design approach is based on the characteristic definitions, not on the feature classifications. The REIMS measurement feature and operation definitions allow the consideration of free-form surfaces whenever there are related topological representation and well-defined manufacturing operation definitions. The same argument applies for the surface roughness measurement as the REIMS structure allows the formation of measurement process definition for roughness evaluation, however, such statement requires further testing.

Another limitation of REIMS is that it only considers the specifications related to a single part and hence excludes the design characteristics that may be specified for assembly and between different parts. Assembly characteristics are used for controlling allowed kinematics between different parts based on five contact types that are classified based on the allowed relative motions, as presented in ISO 25378 (ISO 2011j).

This research developed a prototype implementation to prove the introduced concepts and their potential value for industry. This is a limitation as a computer software package based on the implementation may be required to test complications arising from practical linking issues with commercial CAx systems.

There are also some technology based limitations in the proposed data model. The implementation of some aspects of the model such as non-contact extraction operations requires additional testing as, due to lack of resources, the detailed requirements of various measurement equipment of this type was not comprehensively studied. The flexible philosophy of the data model, however, would allow the necessary additions to be made without affecting the main REIMS structure.

From the ISO standards perspective, it is important to remember that the proposed model is an ARM data model and thus incorporating it within the STEP framework would not be possible without interpreting it into AIM.

9. Conclusion and future work

This thesis has documented the introduction, realisation and implementation of a resource independent measurement specifications (REIMS) framework as a novel and universal paradigm for enabling the interoperable exchange of measurement process definitions at the measurement planning-execution data-connecting interface. This chapter presents conclusions from this research and outlines areas for further investigation.

9.1. Conclusions

Interoperability has been proven to have positive impacts on manufacturing as a cost-saving enabler. At the moment, the measurement process lacks interoperability at the planning-execution data interface. Consequently, it is not possible to exchange the measurement process definitions between different industrial locations in the distributed manufacturing environment. This results in variabilities in the measurement process definitions; hence, causing variabilities in the gained measurement knowledge about products and processes.

This thesis proposed the REIMS data model to allow digital manufacturing experts to transfer measurement process information between various CAx systems. The REIMS data model is resource independent and therefore provides sufficient flexibility to execute a measurement plan using various measurement resources provided that they use the same measurement technology.

This thesis used the STEP modelling and implementation method for developing the REIMS data model. STEP has been chosen as a pre-validated standardised framework for ensuring interoperability in both design and machining applications. In addition, by basing on STEP, the developed measurement schema used the same entity definition introduced in both the geometry and machining schema; this enables the integration and direct harmonisation of the developed data model with both design and machining tasks and hence achieves the modern evolving role of the measurement process.

The ISO GPS was used as the theoretical foundation of the REIMS data model. ISO GPS is the only standardised framework that considers both specifications and measurements as related activities. The ISO GPS objective is to reduce the ambiguity of design specifications and to relate them explicitly to measurement practise and resources.

A prototype implementation of the designed data model proves that the model fulfils the stated requirements and fits the purpose for which it was designed. The prototype implementation is based on the NIST CTC-01 test case that was used for testing the exchange of PMI data between CAD systems. The implementation shows the ability of the REIMS data model to map design specifications represented as AP242 data into measurement features. In addition, it was shown that the REIMS data model is able to represent a variety of measurement operations covering a wide representation of the different operations carried out in industry.

The adoption of REIMS as part of the STEP suite of standards would enable hitherto inaccessible levels of integration between design, machining and measurement to be achieved. The tight integration of measurement working steps in a machining process plan and contextual linking of design characteristics to the result of measurement operations would enable the evolving role of measurement and its transition from a necessary step to a knowledge generating, value-adding process. The resulting framework can initiate a paradigm shift and enable future generations to be able to focus on specifying, “what is required” rather than “how it should be made and measured”.

9.2. Future work

A number of research areas were identified in the course of the work with potential for further investigation to extend the benefits of the approach presented in this thesis. These areas can be summarised as:

1. Extension of REIMS to other measurement technologies and scenarios

Although the REIMS data model has presented, for the first time, non-contact measurement technology based on the dimensionality of the applied measurement sensor, further implementation testing is required to prove the validity of this representation as done in this work for contact triggering and scanning technologies. Many non-contact technologies exist today; hence, various implementation scenarios are necessary for validating, modify or extend definitions presented in this research to make sure that the information model is sufficiently comprehensive. Additional implementation testing of REIMS would be required to confirm the validity of the model in reverse engineering scenarios. More complex specifications and special cases of design specification should also be considered in future implementations to prove the breadth of the REIMS data model and its applicability.

2. Capturing measurement rules and common practice

This research realised the representation of measurement features and operations that serve the purpose of data exchange of measurement process that is defined automatically or manually. For moving further toward the automation goal, measurement rules and practise should be documented, standardised and represented in REIMS. This would allow the automatic construction of measurement operations for a correctly defined and mapped design specifications and measurement features from design stage into the measurement phase. In addition, default values should be defined for each defined parameter in each measurement operation. This is to accommodate the currently applied practice during the design phase in which ISO GPS has not been adopted. STEP provides the necessary constructs in the form of rules and constraints for augmenting REIMS to include this additional information.

3. Embedding conditions in REIMS for self-validation of CAIP data

Additional constraints may be added to REIMS to limit the defined measurement data to feasible populations of entities to represent what is possible in measurement practice. These constraints can then be used to ensure the validity of the published measurement data from a specific CAIP system. With this addition, if a measurement process conforms to REIMS compliance; it would be possible to execute it given the appropriate resources.

4. Representation of measurement results

REIMS has defined the necessary measurement data required for guiding the measurement execution phase. The measurement analysis operations are defined to manipulate data based on the reported values from the execution phase. This reported data needs to be defined and constrained for various expected measurement results to complete all the data that exists within the measurement phase.

The author recommends that measurement results data should be populated in separate files rather than those used in the measurement process definition as one measurement process definition can produce several measurement results from several measurement runs. This was the strategy considered while developing the REIMS data model; that many measurement results can be associated with one measurement extraction or analysis operation and through association to the related nominal measurement feature. The format and mechanism for storing result files need to be defined and tested for standardisation to make sure that all REIMS compliant systems would be interoperable. Coding the results in separate files solves the limitations faced by part 16 (ISO 14649-16) and AP219 (ISO 10303-219).

5. Measurement resource modelling

REIMS provides a resource independent measurement plan that can guide resource selection. This selection process requires information about the available resources and their capabilities. A data model using the same methodology as REIMS - in a similar manner to ISO14649-201 for machining - can be defined to contain such information to be used by process planning, scheduling and factory automation systems. The model can also be used to demonstrate measurement capabilities of a manufacturing enterprise to potential clients allowing distributed, internet of things based and cloud manufacturing systems to be realised.

6. Integrated implementation of REIMS in the production environment

The REIMS data model has identified, defined and represented data necessary for measurement process definition. The published REIMS data may require further investigation to be adapted to the available commercial software languages and applications. This includes translation mechanisms of REIMS data to other languages such as DMIS, G&M codes or XML. Providing these tools would extend the industrial applicability of REIMS.

7. Investigating the effects of adoption of the REIMS framework in future design and manufacturing practice

Future research could consider the assessment of the benefits that could be gained from the REIMS measurement data within the product lifecycle in a more profound manner. This includes the assessment of REIMS as an enabler for controlling machining processes for more adaptable and dynamic process planning systems for more responsive manufacturing systems. This also includes identifying the scope and requirements of the measurement data to modify design decision based on the measurement of initial design prototypes toward a final design that is optimised with respect to available machining and measurement resources.

8. REIMS measurement machines

The introduction of REIMS based controllers for measurement devices would enable the reduction of the currently applied translation solutions between planning and execution steps that have effects on both cost and accuracy. As REIMS is designed in a STEP-compliant manner, wide adoption of REIMS in conjunction with ISO10303-238 would cause a paradigm shift toward smarter, more responsive and customisable production systems. Realisation of REIMS and STEP-based machines will benefit the digitalisation trend and simulation capabilities and hence enhances optimised product and processes with respect to factors such as cost, time and quality.

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Appendix A. Publications

1. Hesham Mahmoud, Vimal Dhokia, Aydin Nassehi, “STEP-based Conceptual Framework for Measurement Planning Integration”

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Measurement aims to check the product conformance or to control the manufacturing processes’ parameters. It needs to be planned in an integrated and interoperable manner with other manufacturing activities. Integration of measurement planning is based on the information provided by the design phase. This paper aims to assist the interoperability of the measurement plans through introducing the resource-independent measurement specifications (RIMS) concept. The paper presents a conceptual framework for representing a STEP-based measurement features from the coordinate metrology perspective. The proposed framework supports the direct formulation of the measurement process specifications in an operation-based manner and the realization the process control functionality of the measurement processes.